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The recovery of copper from automotive wiring harnesses.

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THE RECOVERY OF COPPER FROM AUTOMOTIVE WIRING HARNESSES

by

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ABSTRACT

Auto manufacturers have set a goal for the technical recyclability and recovery of new vehicles that requires as much as 95% of the vehicle weight to be diverted from landfill in a technically and economically feasible manner. In order that future vehicles achieve this goal, which is in line with the draft European Union End-of-Life Scrap Vehicle Directive, it will be necessary to develop a system to recycle all vehicle electrical wiring harnesses. This paper describes the development of a process that uses a cryogenic method of separating the non-metallic insulation from the metallic conductor material.

This thesis investigates the potential for the development of a unique process to recycle automotive wiring harnesses. As part of the design approach, a cryogenic testing chamber was constructed along with a mechanical wire crusher to remove the insulation from the wires. Two tests were performed, which consisted of a "Complete Wiring Harness Test" and a "Wiring Harness Material Test".

Analysis of the Complete Wiring Harness Test, revealed that there were certain polymers used on automotive wiring harnesses which were unable to reach their glass transition temperature. Therefore a second test, referred to as The Wiring Harness Material Test, was performed to reveal which materials were unable to reach the glass transition temperature in order to allow for the recovery of copper. Finally, the results and information gained in this research have advanced the possibility of future successful development of a mechanical process to remove the insulation from automotive wiring harnesses, which would allow for the recovery of copper.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

ARDC – Automotive Research and Development Center

ELVs – End-of-Life Vehicles

USCAR- United States Council for Automobile Research

ASR- Automotive Shredder Residue

DFR- Design for Environment

ISO- International Organization for Standardization

DFE – Design for the Environment

PVC – Polyvinyl Chloride

$CACO_3$ - Calcium Carbonate

CARE – Concepts for Advanced Recycling and Environmental Solutions

PC – Polycarbonate

PBT – Polybutylene Terephthalate

PBT + PC – Polybutylene Terephthalate/ Polycarbonate blend

PA – Polyamide

PET – Polyethylene Terephthalate

EPDM – Terpolymer of ethylene, propylene, and a diene

1 Introduction

The purpose of this project is to conduct research directed towards recycling automotive electrical wiring harnesses. This is a unique project that involves the recovery of copper found in wiring harnesses. The research project is being conducted in conjunction with the University of Windsor/DaimlerChrysler Canada Automotive Research and Development Centre (ARDC), and has come about through anticipated future legislation aimed at the recycling of motor vehicles. Vehicle recycling is a sensible way for automakers to achieve both internal and external economic and environmental goals. The European Union policy towards environmental protection is to increase the recovery of these End-of-Life Vehicles (ELVs) over the next twenty years. The voluntary take-back legislation requires all automakers to buy back vehicles from their owners at the end of the vehicles life. The vehicles would then be delivered to automotive dismantlers where they would be disposed of in an environmentally friendly manner. Strict domestic and international labeling and reporting requirements for plastics and hazardous substances, has prompted automotive manufacturers to aggressively evaluate the regulated substances contained in their automobiles and the recyclability of their automobiles. The auto industry is developing strategies to reduce the hazardous substance content of the vehicles and manufacturing processes to improve vehicle recyclability in a cost-effective manner.

The project came about after intensive research into the approaches developed by the United States Council for Automotive Research (USCAR) consortia which was a partnership jointly developed by Ford Motor Company, General Motors Corporation and

Chrysler Corporation (now DaimlerChrysler), in 1991. The recycling group opened the Vehicle Recycling Development Centre (VRDC) in Highland Park, Michigan, in January 1994 and DaimlerChrysler's Vehicle Recycling Laboratory and Analysis was transferred to the Automotive Research and Development Centre in June of 1999.

The idea of recovering copper from wiring harnesses utilizing the method of cryogenics was a topic of great interest for the recycling group. Research material was collected in order to acquire knowledge of all the current recycling methods used on wiring harnesses.

The proposed project consists of developing a mechanical process under cryogenic conditions to separate automotive harnesses into two different material categories, copper and insulation material, which consists of a mixture of polymers. This is a unique project since other recycling methods for wiring harnesses are found to be hazardous for the health, too costly, or produce a mixture of copper and plastic remainings which are very difficult to separate.

1.1 Definition of a Wiring Harness

The "wiring harness" is the nervous system of a vehicle; it is the single unifying structure linking the driver to the vehicle and the vehicle to the driver. More than 5000 components and over three kilometers (two miles) of wire embody a typical vehicle electrical distribution system. The wiring harness is a very complex system connecting each electrical device and reacting to the driver's needs. It essentially makes the driver and vehicle one.

Wiring harnesses provide two major functions in a vehicle:

a) distribution of power from the source to the load

b) transmission of information, for example

-a switching command

-information relating to vehicle performance parameters, such as coolant temperature, fuel level, oil pressure, etc.

Generally, power is distributed from the fascia panel to several switches, which are positioned so that they may receive a switch command from the "commander"(i.e. the driver). Separate wires, carrying power and commands to the appropriate load or device take the output from each of these switches. When a switch is in another part of the car body (e.g. the interior light-switch), power is fed from the source through the switch to the load.

Below is a figure showing typical wiring harness found in the dashboard of an automobile.

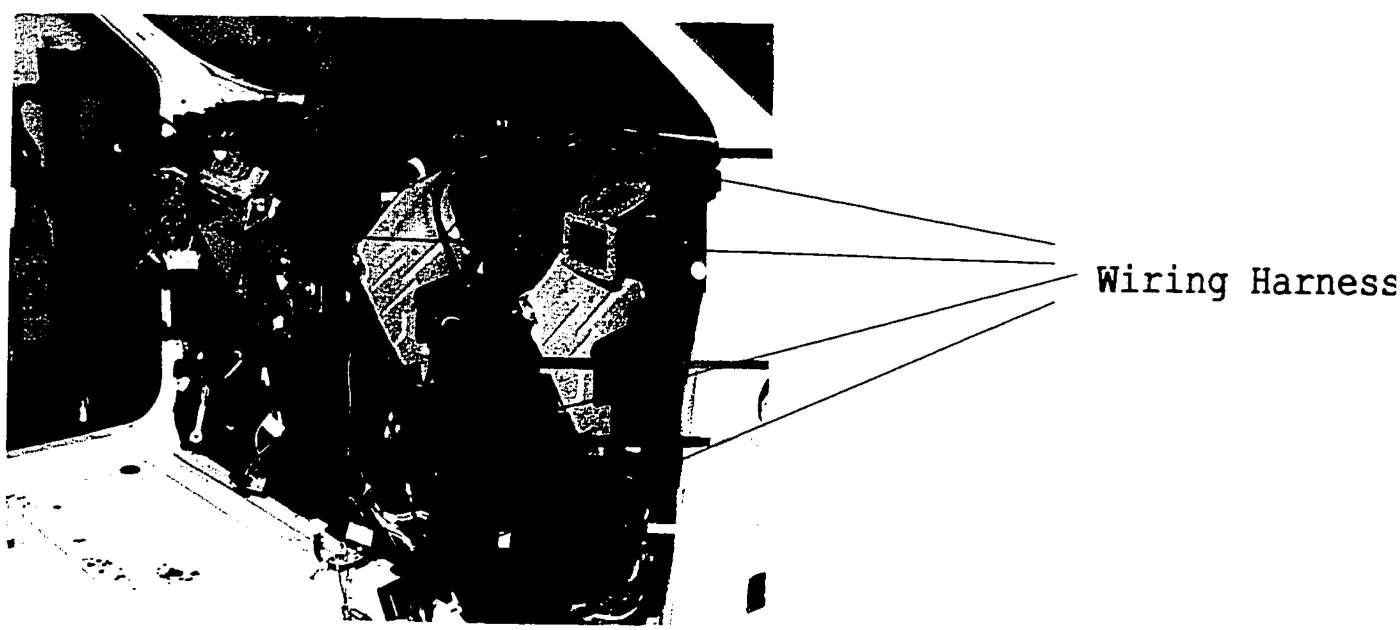


Figure 1-Automotive Dashboard Wiring Harness

Figure 1 shows the amount of wiring harness that can be recovered from the dashboard of a 1998 Plymouth Voyager Minivan.

A typical instrument panel environment encompasses approximately 150761 cm^3 (9200 in^3) of space into which on the order of 93 components are packaged. Of the area, 65% is occupied by the mechanical and functional components such as the cluster, radio, A/C system, and other devices, 12% is occupied by electrical hardware, and 2% is occupied by the necessary wiring harnesses [18].

Instrument panels also have an average clearance between components of approximately 12.7 mm (½ in), but there exist a severe packaging problem in the total area; Only 22% of the available space is left for miscellaneous brackets, supports and essential access space for servicing components under the panel.

As the industry trend moves toward smaller, more compact vehicles, human factors such as safety, component weight and size problems become more difficult to solve.

Compact vehicles are smaller in size, therefore they have a more restricted interior packaging for the driver and the front seat passengers. These conditions directly affect the width of the vehicle's instrument panel area where the displays and controls can be located. As automotive complexity has increased, the lengths of wiring harnesses have significantly increased. In recent years, the total increase in copper content per car has been about 5% each year. As the automobile becomes more and more technologically advanced, manufacturers in the wiring harness and connector market must continually develop new technologies to remain competitive. Any new technology chosen to replace or supplement the present design practice must assist the designer to solve human factors and component packaging problems. These may consist of new technologies that assist designers to create new and different instrument panel designs at a lower cost. If a set of program objectives to meet these criteria were developed, major emphasis would be placed on reducing packaging size and weight for all components, a smaller, less complex vehicle electrical system and a reduction in the number of unique components by combining functions wherever possible.

The wiring harness and connector markets are being driven by the increased electrical and electronic content of vehicles, such as safety, comfort, and convenience features, including navigation, information and entertainment systems. The introduction of electrical and electronic systems like electronic throttle control, electric steering and electric braking are also expected to affect the market.

As the number of applications for wiring harnesses increase, so does their complexity. However, in this market, it is difficult for suppliers to pass the increased cost to automobile manufacturers, and ultimately customers, through higher prices. Automakers need to control vehicle prices while offering more and more features. Thus, they are very price sensitive while striving to provide better components at low costs every year.

The wires found in wiring harnesses are colour coded to make it easier to determine what the wire operates and what it is connected to. Figure 2 is a schematic of some wires showing the different colours found in an automobile. Included is a table of the entire standard wiring colours and their associated functions.

Figure 2-Wire Colours

WIRING COLOR CODE TABLE

MAIN	TRACER	PURPOSE
Black		All ground connections
Black	Blue	Tachometer generator to tachometer
Black	Red	Electric or Electronic speedometer to sensor
Black	Purple	Temperature switch to warning light
Black	Green	Relay to radiator fan motor
Black	Light green	Vacuum brake switch or brake differential pressure valve to warning light and/or buzzer
Black	White	Brake fluid level warning light to switch and handbrake switch, or radio to speakers
Black	Yellow	Electric speedometer
Black	Orange	Radiator fan motor to thermal switch
Blue		Lighting switch (head) to dip switch
Blue	Brown	Headlamp relay to headlamp fuse
Blue	Red	Dip switch to headlamp dip beam fuse
		Fuse to right-hand dip headlamp
Blue	Light Green	Headlamp wiper motor to headlamp wash pump motor
Blue	White	a) Dip switch to headlamp main beam fuse
		b) Headlamp flasher to main beam fuse
		c) Dip switch main beam warning light
		d) Dip switch to long-range driving light switch
Blue	Yellow	Long-range driving light switch to lamp
Blue	Black	Fuse to right-hand main headlamp
Blue	Pink	Fuse to left-hand dip headlamp
		Headlamp main beam fuse to left-hand headlamp or inboard headlamps when independently fused
Blue	Orange	Fuse to right-hand dip headlamp
Brown		
Brown	Blue	Main Battery lead
Brown	Blue	Control box (compensated voltage control only) to ignition switch and lighting switch (feed)
Brown	Red	Compression ignition starting aid to switch
		main battery feed to double pole ignition switch
Brown	Purple	Alternator regular feed
Brown	Green	Dynamo 'F' to control box 'F'
		Alternator field 'F' to control box 'F'
Brown	White	Ammeter to control box
		Ammeter to main alternator terminal
Brown	Yellow	Alternator to 'no charge' warning light

Brown	Black	Alternator battery sensing lead
Brown	Slate	Starter relay contact to starter solenoid
Brown	Orange	Fuel shut-off (diesel stop)
Green		Accessories fused via ignition switch
Green	Brown	Switch to reverse lamp
Green	Blue	Water-temperature gauge to temperature unit
Green	Red	Direction indicator switch to left-hand flasher lamps
Green	Purple	Stop lamp switch to stop lamps, or stop lamp switch to lamp failure unit
Green	Light Green	Hazard flasher unit to hazard pilot lamp or lamp failure unit to stop lamp bulbs
Green	White	Direction indicator switch to right-hand flasher lamps
Green	Yellow	Heater motor to switch single speed (or to 'slow' on two-or three speed motor)
		Fuel gauge to fuel tank unit or changeover switch or voltage stabilizer to tank units
Green	Pink	Fuse to Flasher unit
Green	Slate	a) Heater motor to switch ('fast' on two-or three speed motor)
		b) coolant level unit to warning light
Green	Orange	Low fuel level switch to warning light
Light Green		Instrument voltage stabilizer to instruments
Light Green	Brown	Flasher switch to flasher unit
Light Green	Blue	a) flasher switch to left- hand flasher warning light
		b) Coolant level sensor to control unit
		c) Test switch to coolant level control unit
Light Green	Red	Fuel tank changeover switch to right-hand tank unit or entry and exit door closed switch to door actuator
Light Green	Purple	Flasher unit to flasher warning light
Light Green	Green	Start inhibitor relay to change speed switch; or switch to heater blower motor
		second speed on three-speed unit
Light Green	White	Low air pressure switch to buzzer and warning light
Light Green	Yellow	Flasher switch to right-hand warning light; or differential lock switch to differential lock warning light
Light Green	Black	Front screen jet switch to screen jet motor
Light Green	Slate	Fuel tank changeover switch to left-hand tank unit; or entry and exit door open switch to door actuator
Light Green	Orange	Rear window wash switch to wash pump; or cab lock-down switch to warning light
Orange		Wiper circuits fused via ignition switch
Orange	Blue	Switch to front screen wiper motor first speed timer or intermitted unit
Orange	Green	Switch to front screen wiper motor second speed
Orange	Black	Switch to front screen wiper motor parking circuit, timer or intermitted unit
Orange	Purple	Timer or intermittent unit to motor parking circuit
Orange	White	Timer or intermittent unit to motor parking circuit
Orange	Yellow	Switch to headlamp or rear window wiper motor feed, timer or relay coil
Orange	Light Green	Switch to headlamp or rear window wiper motor parking circuit timer or relay coil
Orange	Pink	Timer or relay to headlamp or rear window wiper motor feed
Orange	Slate	Timer or relay to headlamp or rear window wiper motor parking circuit
Pink	White	Ballast terminal to ignition distributor
Purple		Accessories fed direct from battery via fuse
Purple		Horn fuse to horn relay when horn is fused separately
Purple		Fuse to heated rear window relay switch and warning light
Purple		Switches to map light, under bonnet light, glove box light and boot lamp when fed direct from battery fuse

Purple		Fuse to hazard flasher
Purple		Fuse to relay for screen demits
Purple		Interior light to switch (subsidiary circuit door safety lights to switch)
Purple		Horn to horn relay
Purple		Horn to horn relay to horn push
Purple		Rear heated window to switch or relay
Purple		Aerial lift motor to switch up
Purple		Aerial lift motor to switch down
Red		Main feed to all circuits mastered by sidelamp switch
Red	Brown	Rear fog guard switch to lamps
Red	Blue	Front fog lamp fuse to fog lamp switch
Red	Purple	Switches to map light, under bonnet light, glove box light and boot lamp when sidelamp circuit fed
Red	Green	Bulb failure unit to right-hand side and rear lamps
Red	White	a) Sidelamp fuse to right-hand-side and rear lamps b) Sidelamp fuse to lighting relay c) Fuse to panel light switch or rheostat d) Fuse to fibre optic source
Red	Yellow	Fog lamp switch to fog lamp or front fog fuse to fog lamps
Red	Black	Left-hand, sidelamp fuse to side and tail lamps and number plate illuminations
Red	Pink	Sidelamp fuse to lighting relay
Red	Slate	Lamp failure unit to left-hand side and tail lamps
Red	Orange	Fusebox to rear fog guard switch
Slate		Window lift main lead
White		Ignition switch or starter solenoid to ballast resistor
White	Brown	Oil pressure switch to warning light or gauge, or starter relay to oil pressure switch
White	Blue	Choke switch to choke solenoid (unfused) and/or choke switch to warning light, or electronic ignition distributor to drive resistor
White	Red	Starter switch to starter solenoid or inhibitor switch to starter relay or ignition (start position) to bulb failure unit
White	Purple	Fuel pump no 1 or right-hand to changeover switch
White	Green	Fuel pump no 2 or left-hand to changeover switch
White	Light Green	Start switch to starter interlock or oil pressure switch to fuel pump or start inhibitor switch to starter relay or solenoid
White	Yellow	Ballast resistor to coil or starter solenoid to coil
White	Black	Ignition coil contact breaker to distributor contact breaker, or distributor side of coil to voltage impulse tachometer
White	Pink	Ignition switch to radio fuse
White	Slate	Current tachometer to ignition coil
White	Orange	Hazard warning lead to switch
Yellow		a) Overdrive b) Fuel Injection c) Door Locks d) Gear selectors switch to start

Table 1- Wiring Color Table (from [15])

1.2 The Necessity of Recycling Wire Harnesses

The wiring harness is the most expensive component of the vehicle's electrical system [11]. With the prospect of electrical power loads exceeding 1 kW, this will require designers to use larger wire gauges, resulting in a dramatic weight and cost increase.

Since copper is a widely used material with a significant commercial value, being able to recover and reuse it is important.

The average price of a wiring harness can range from $500 to $1000 depending on its function and its location. Wiring Harnesses can be located in three major areas of a vehicle, the engine compartment, the interior compartment, and under the vehicle's body. There is approximately 15-20 kg of wiring harness that can be removed from an automobile. Close to 45% of this mass is copper and the remainder is insulation material and connector bodies. Thus an average car contains approximately 9 kg (nearly 20 lb.) of copper. Recycled copper can be sold for $2.20, therefore there is a potential for saving $19.80/vehicle.

DaimlerChrysler has set ambitious goals for new vehicles introduced in 2002 to be 85% recyclable, 5% of which is energy recovery and the remainder will consist of Automotive Shredder Residue (ASR). The target increases to 95% from 2005 through 2010. With the prospect of vehicles being able to achieve this recyclability rating, it is of utmost importance to have an infrastructure in place to recycle wiring harnesses. This infrastructure will have to be both cost-effective and environmentally friendly. The development of harness recycling methodology will assist in the development and maintenance of comprehensive vehicle recycling programs.

2 Literature Survey

2.1 Background Research On Vehicle Recycling

2.1.1 Introduction

Recycling implies that material is processed out of one form and remade into a new product. Automakers have been recycling since the days of Henry Ford, but it was not until the early 1960s that recycling became a subject of national interest. Vehicle disposal made the national agenda when abandoned cars began to pile up in junkyards and along the sides of highways. While policy makers argued over a legislative solution to this problem, the abandoned car crisis had begun to resolve itself through technological innovation. Vehicle recycling is a sensible way for automakers to achieve both internal and external economic and environmental goals. By using recycled components in the manufacturing of new vehicles, they can reduce costs for both the consumer and themselves, as well as conserve valuable resources.

Every year approximately 400,000 automobiles are taken off the road in Ontario [9]. When the automobile is no longer of use to its owner, it commonly is sold or given to an automobile dismantler. The vehicles are usually eight to 10 years old and range in size from large trucks to family cars. They can be in relatively "good" condition, with many reusable parts, or in such damaged or poor condition as to yield few reusable components and be suitable only as scrap material. Vehicle recycling today is carried out primarily by two types of operations know as, automobile dismantlers and automobile shredders. Figure 3, shows a flowsheet which dismantlers follow when a vehicle has reached the end of its useful life. The Expired Vehicle Flowsheet shows that dismantlers are restructuring their operations and adopting an "organized dismantling" approach to scrap vehicle management.

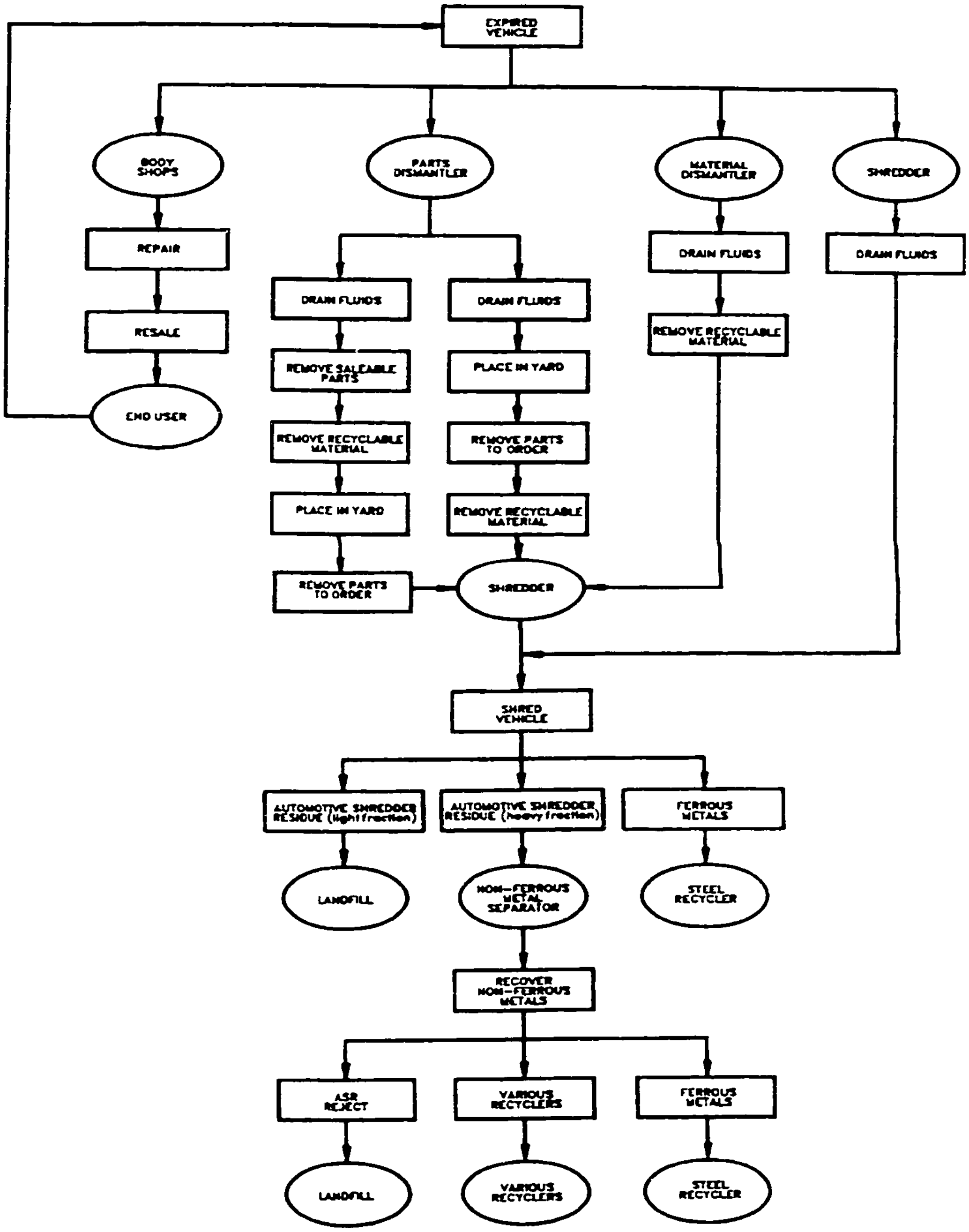


Figure 3 –Expired Vehicle Flowsheet (from [8])

2.1.2 The Automobile Recovery System

Automobiles typically enter the recycling system by way of an automotive dismantler, to whom vehicles are commonly sold when they are no longer useful or are damaged beyond repair in a collision. Inoperative motor vehicles are brought into the facility and the hazardous and recyclable fluids are properly drained from the vehicle. Undamaged parts are then dismantled from the vehicle, cleaned, tested, inventoried, and stored in a warehouse until sold. These parts include engines, starters, generators, and other mechanical parts, which are typically reconditioned for resale. Batteries (for lead and polypropylene), and catalytic converters (for platinum, rhodium and stainless steel), are examples of components that are removed and sold for further processing. A large number of metal and plastic parts from taillight assemblies to fenders are removed and resold into the used parts market. Plastic parts, which are components of larger assemblies (such as doors, front ends, seats, etc.), are typically sold as part of the complete assembly. Other plastics remain in the stripped vehicles, which are usually stored in outside yards.

Dismantlers typically sell used parts at half of the price of new parts available from dealerships. Increasing competition and environmental pressures are compelling dismantlers to diversify and specialize. Consequently, more and more dismantlers are restructuring their operations and adopting an "organized dismantling" approach to scrap vehicle management. Professional auto recyclers use computer and satellite communication systems that enable for direct inventory assessment as well as locate parts across town or across countries, by simply entering the appropriate data. This procedure provides quick and efficient service to their customers. The remaining vehicle body is then prepared for scrapping.

The shredder, an expensive and often sophisticated piece of equipment, reduces the car to small fragments within seconds. The scrap processors recover most of the metals, which are recycled back into new steel and nonferrous metal products. This amounts to approximately 75% of the mass of a typical vehicle [3]. The remaining materials are known as "fluff" or automotive shredder residue (ASR). The ASR consists of all of the plastics, foam, glass, rubber, residue fluids, residue metals, and the dirt acquired during usage, and is currently landfilled. Fragments are sorted mechanically into ferrous and non-ferrous materials. The latter are further sorted by density into metallic and nonmetallic fractions. Recyclable materials from the shredding process are sold to metal processors, mills, foundries and other manufacturers for reuse in new products.

2.1.3 Economic Aspects of Automobile Recycling

A product that is recyclable may or may not be recycled. Recyclability refers to a product possessing properties that makes it technically possible to recycle. Recycling is the actual process of recovering materials, components or other resources, such as energy, from a recyclable product. Therefore recycling is strongly related to technology and economic feasibility, but, because it does not occur unless the participants can make profits, which implies that it is mainly an economic activity [2].

The recycling infrastructure is complicated; it consists of many organizations. A further complication is that most of the organizations in automotive recycling are involved in the recycling of other products including: washing machines, plumbing fittings and electronic devices. If appliance recycling is a recycler's major business and automotive recycling secondary, his corporate viability might be influenced only slightly by legally mandated actions dealing with automotive material or automotive recycling economics.

2.1.4 Design for Recycling

Today's recyclers deal with vehicles and infrastructure components that were designed with little or no thought as to their recyclability. As a consequence, many of the materials are difficult to recover in pure or usable form, many components are difficult to reuse, and many parts of the vehicle are hard to separate. Major improvements are possible if design engineers include "design for recycling" as part of their design process.

When planning for product-end-of-life, two complementary types of recycling should be considered. Closed loop recycling involves reuse of the materials to make the same product over again. A typical example is reprocessing used aluminum cans to make new aluminum cans. The alternative is open loop recycling, a typical example of which is the use of discarded office paper to make brown paper bags. The mode of recycling will depend on the materials and products involved, but closed-loop recycling is generally preferred, since many consumers do not desire or choose to purchase recycled products.

Design for Recycling (DFR) should focus on a small number of rules:

a) minimize the use of different materials,

b) choose desirable materials, considering not just manufacturing and use characteristics, but recycling potential as well,

c) make the product modular,

d) eliminate unnecessary product complexity,

e) make the product efficient to disassemble,

f) make the materials easy to recover [3].

These rules are discussed in detail below.

Minimize the Use of Materials

In a "less is better" philosophy, design goals should be accomplished by the use of minimal amounts of materials. The strength desired in a component or panel can be achieved with ribs and bosses rather than heavy-gauge materials. Advanced materials, with improved structural characteristics, can provide the desired degree of stiffness with less material. Detailed stress analysis may demonstrate that less material is needed, than has customarily been used, in order to meet strengthened stiffness requirements.

Minimize Material Diversity

Any article as complex as an automobile inevitably requires the use of many different materials. Frequently, however, material selection is not optimized across the automobile design as a whole, with the result that a greater variety of materials are used than cost and performance require. The vehicle may therefore be more difficult and expensive to recycle from a technical standpoint.

Choose Desirable Materials

Automotive materials have always been chosen with performance characteristics in mind, but the environmental aspects of materials should enter into the choices as well. A key recommendation is to use recycled materials whenever possible. Metals are recycled with reasonable efficiency, and can generally be re-refined to achieve the desired composition. Paper recycling is more complicated by the fact that at each stage of recycling, the paper fibers shorten and restrict the recycled material to lower quality uses. This sequence is known as a cascade recycling. In the case of plastics, the difficulties of separating and reprocessing have made progress slower but research in plastics recycling is growing rapidly [3]. In order to promote the use of recycled materials, the designer should specify to the supplier the material properties rather than their sources. Manufacturers can, in many cases, require suppliers to provide a fixed percentage of purchased material from scrap sources.

In the automobile design, only about five percent of material used at present, is acquired from recycling streams. Recycled steel is currently too impure for the high-strength requirements of many components, and is instead incorporated into lower-grade items such as castings or non-automotive products. Additional efforts on purification of recycled steel, are desirable.

Nearly 80% of the vehicle is recycled in some way, but much of the material can only be used in degraded form. About 15% of the raw material input is eventually landfilled. Regardless of whether the materials used are virgin or recycled, their use is such that their recycling at end of life is optimized [3].

Many biomaterials have excellent mechanical properties at modest weight. Biomaterial use does not deplete non-renewable resources and avoids toxicity problems. Further, when they eventually decompose or undergo incineration, they return to the atmosphere no more carbon dioxide than they absorbed from the atmosphere while growing. The agricultural operations that produce them do have their own environmental impacts, so tradeoffs are involved. Among the uses to which biomaterials are being put in automobiles are shelves, floor mats, interior panels, and interior acoustical padding.

Modular Design

Modularity has always been a feature of automobiles. Shock absorbers, radiators, exhaust systems, and even engines are commonly replaced. Designers can aid in this process by designing for efficient replacement of modules; the use of standard sizes and types of fasteners, and by designing modules so that they may be efficiently recycled, such as by making fluid-containing parts easy to drain and clean.

Manufacturers can readily aid this process by taking a few logical steps that have generally been inhibited by tradition. Mercedes-Benz in Germany, for example, works with repair and collision shops to recover modules for reconditioning or remanufacturing.

If neither is possible, the materials in the modules are recycled. In the longer term, it may be possible for reconditioned or remanufactured components to be given standard "new parts" guarantees and used in new automobiles. A next step in modular design is the creation of systems that permit the upgrading of individual modules while the rest of the automobile remains the same. One might imagine, for example, exchanging control panel and engine modules while retaining the passenger compartment and its heating and cooling system. A few preliminary modular designs suggest that such vehicles may be available in the early 21st century.

Eliminate Unnecessary Complexity

It is well known within industry that far more individual parts than necessary are incorporated into product designs. This not only makes manufacture more complex and expensive, but also makes recycling more environmentally difficult. More parts require more assembly steps and cleaning, which in turn generates more waste streams. Parts complexity can have a similar effect on the recycling end. A profusion of parts makes disassembly more complex, and tends to encourage the use of generic end-of-life technologies such as hammer mills and shredders, which produce larger volumes of low-value ASR than necessary.

Design for Efficient Disassembly

A major factor in recyclability is how easy or difficult it is for a vehicle to be disassembled. Where once parts of vehicles have traditionally been welded or joined in ways that were difficult to reverse, modern fastening technology provides many joint alternatives. For example, joining parts with snaps, clamps or screws is preferable to using welds or glues. Bolts and screws should be positioned so that access to them is relatively easy. Fasteners should be those in common use, recognizing that dismantlers are likely to have on hand only the more common tools.

Fastening techniques, thought to be relatively unconventional are becoming increasingly common. For example, polymeric hook and loop fasteners are used by some manufacturers to affix head linings and interior trim into place. Hook and loop fasteners become only more secure as vehicles flex during use, but the components they join can be readily separated when recycled.

Once materials are disassembled, it is crucial to be able to identify them promptly and reliably. Standard identification markings, such as those for plastics developed by the International Organization for Standardization (ISO), should always be used. Figure 4 shows these symbols.

>PC<	Poly (carbonate)
>PBT<	Poly (butylene terephthalate)
>(PBT + PC)<	Poly (butylene terephthalate)/poly(carbonate) blend
>(PBT + PC)<	Poly (butylene terephthalate)/poly(carbonate) blend; 20% glass-filled

Figure 4 – Standardized markings for plastic parts (from [3])

Marking is also useful for metals, should there be any uncertainty about the metal or alloy from which a component is made.

Since trade impurities can effect the value of scrap materials, and hence their recyclability, designers should try to make materials easy to separate. Copper wiring harnesses, for example, should be easy to strip from auto bodies, and thus avoid the contamination of the steel. Natural minerals such as wood or flax should be easy to separate from plastics or metals.

Choose the Material for Easy Recovery

A major impediment to the recycling of automotive materials is their presence in composites, welded, or glued units that make the individual materials difficult to recover in pure form. Examples of assemblies of materials that constrain recovery are; carbon fibers in a polymer matrix, wood, metal, and polymer mixture in a dashboard. Mixed materials are also a problem with plastics, some combinations are compatible during recycling, and some are not. A second problem is the difficulty in separating otherwise relatively pure materials, such as copper in a wiring harness buried within door panels. In either case, one or all of the mixed materials are unlikely to be economically recoverable.

Copper is a particular problem if not retrieved, since copper impurities inhibit the mechanical properties and the reuse of recycled steel. Although aluminum is a less efficient electrical conductor, it may be a suitable replacement for copper in some current-carrying applications, and fibre optics may be suitable where information rather than electrical current is being transmitted.

A related problem is that of inserts, that is, components that are joined mechanically, such as in metal studs inserted into plastic components. Designs in which this situation occurs are generally unsound from the Design for the Environment (DFE) standpoint. If they must be used, the insert should generally be composed of steel, which can be separated magnetically.

Coatings and platings are examples of the mixing of materials. It is often the case during recycling that such surface treatments are lost, as there is no reasonable means of recovering the plated material. For automobiles, this is particularly true of the zinc used as anticorrosion plating. Careful materials selection can sometimes enable compatible coatings to be used for plastics, and allow metal platings to be recovered. Painting or plating, especially with toxic substances such as chromium, is to be avoided.
Fluid recovery must also be considered in the design process. Although recovery of oil, antifreeze, transmission fluid, and the like is generally practiced, good design can improve the completeness of the recovery process. Drainage points should be easily accessible and fluid reservoirs should be designed for complete drainability. Drainage plugs and access ports should be standardized as much as possible to mate with recovery equipment.

A final point relates to designs that are presumably without mixed materials but which achieve mixing during manufacture. The classic case is that of labels affixed to plastic parts to provide bar codes, mandated consumer information, safety instructions, and the like. Very often, these labels are difficult and time-consuming to remove, and they may irretrievably contaminate the base material they are attached to. The solution is to make the labels easily strippable, to make the labels from the same plastic as the part itself, or to fasten them onto a small portion of the component that is designed to be broken off and discarded during recycling.

2.1.5 German Developments in Recycling

The German government in the 1991 revision of the Waste Avoidance and Waste Management Act of 1986, first proposed the concept that manufacturers takes back products such as cars in the same ways that soft drink bottlers take back empty bottles [6]. That act required manufacturers to assume responsibility for the total life cycle of products, including taking back products after use and initiating product-recycling loops. One important goal in initiating this legislation is to force industry to take full responsibility for the life cycle of its products. The government hopes that a (DFE) mentality will encourage a pollution-prevention approach to addressing environmental problems.

By forcing industry to be responsible for the disposal of its products, the government intends to place the financial burden of disposal clearly on industry's shoulders. This will give industry the incentive to employ design-for-environment (DFE) techniques, manufacture products that have minimum environmental impact, and reduce disposal costs. Design for recyclability may be more expensive to consumers because auto manufacturers will pass on the added recycling costs to the consumer by raising the retail price of their vehicles. On the other hand, if industry fails to assume responsibility for the disposal of its products, the government's initiative will likely fail.

Pressure to focus on the automobile has increased recently because of scarce landfill space and high fees. In addition, the automobile is a highly visible product that produces environmental, noise, and traffic pollution during its manufacture, use, and disposal. In addition, the number of automobiles produced every year is increasing.

Policy Requirements

a) Motor vehicle manufacturers and dealers or commissioned third parties will collect scrapped vehicles from end users;

b) the end user must be allowed to return the vehicle at no charge;

c) recycling and reuse of materials and parts are to have priority over other methods of disposal, given that they are technically possible, reasonable in terms of cost, and have existing or potential markets;

d) responsible parties must ensure creation of the required facilities for dismantling these vehicles and recycling or reuse of parts and materials

e) recycling and reuse must be taken into account during the initial design of the vehicle[6]

This policy places several requirements on the German automotive industry. The industry must not only accept scrap vehicles from consumers regardless of the vehicle's condition, but must do so without charge to the consumer. The manufacturer must ensure that a proper infrastructure has been established to accommodate the necessary materials dismantling, sorting, and recycling. In addition markets must be developed for these materials, with an emphasis on closed-loop materials recycling. This must be accomplished concurrently with the implementation of new design techniques that will facilitate vehicle recycling. The government plans to allow automakers to add the cost of disposal onto the initial price of the vehicle to lessen their burden.

2.1.6 Current Wire Harness Recycling Methods

There are a number of programs underway today with regards to recycling of wire harnesses, and these are described below.

Method 1

Wire Harnesses are chopped into pieces using a "Chopping Machine", (a rotary blade process); this is shown in Figure 5 below. This machinery is able to granulate insulated copper wire, simultaneously separating the plastic from the copper. It is possible to produce up to 5,000 pounds an hour of finished product with this specialized equipment. The finished product consists of separated plastic and copper.

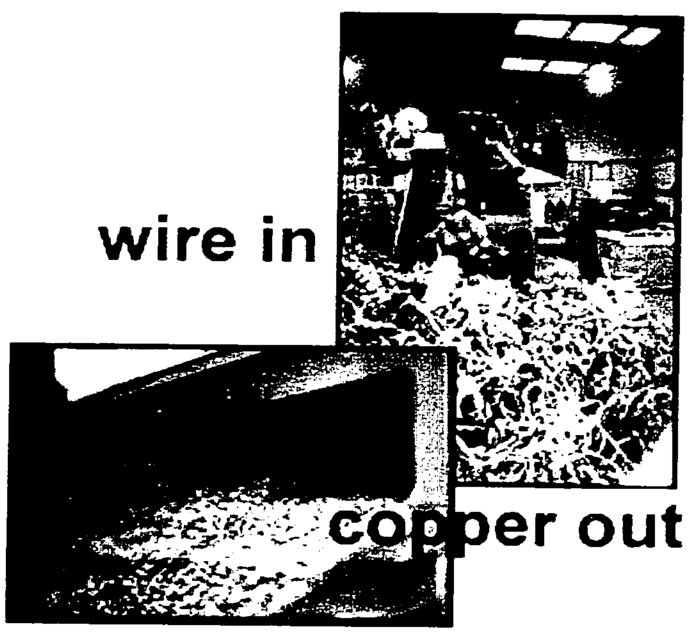


Figure 5- Chopping Machine (from [4])

Method 2

Yazaki Corporation is the leading electrical system supplier to the automotive industry, and has focused on and addressed the design category of resin reduction, consolidation and elimination of all poly-vinyl chloride (PVC) material. Yazaki's goals were achieved through reduction of the wiring harness components in the 1998 model year DaimlerChrysler JA platform vehicle (Plymouth Breeze) and then by reduction of the materials amongst those various components. There are currently over 18 different materials used in the JA wire harness components. The materials were consolidated to 9 resulting in a reduction of 50%. Material consolidation refers to reducing the number of plastic families used in the harnesses, with reduction more related plastics are used which have the same properties therefore allowing easier recycling methods. The plastics were further consolidated to 2 different material families, which has improved the ability to recycle the wiring harness.

The consolidated material offers additional benefits related to recycling. In addition to a material consolidation of 50%, Yazaki has eliminated all PVC materials from their wiring harnesses. PVC's are self-extinguishing, however they produce toxic chemicals when burned and use of this material should be minimized. PVC's show marked deterioration after several years in the presence of soil micro-organisms, the application of composting techniques to plastics is usually ineffective because of their biological inertness.

Method 3

Mechanical shredding are used for reducing insulated wire to an aggregate containing bits, particles, and pieces within a required size range. Extraneous magnetic materials are removed and the content of resin coating material is reduced under dry conditions. The process is shown schematically in Figure 6 below.

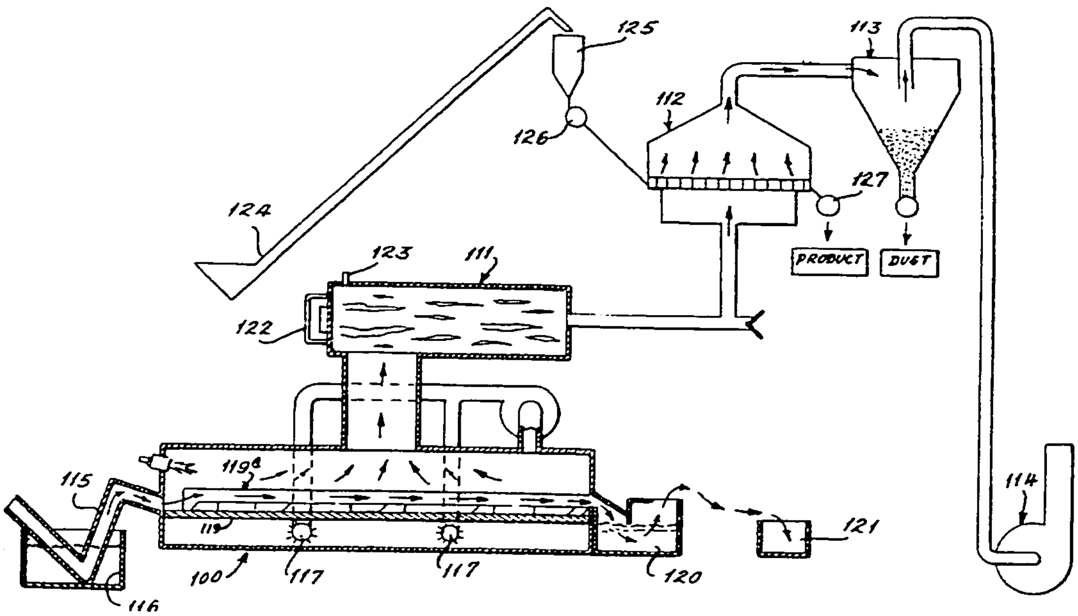


Figure 6- Process for Pyrolyzing Vinyl Chloride Insulation from Copper Wire (from [14])

This shows a system compromised of a decomposition chamber, (number 100), an afterburner (111), a fluidized bed reactor (112), a dust collector (113), and an induced draft fan (114). The chopped input material which consists of insulated copper wire containing polyvinyl chloride insulation, is continuously fed at a rate controlled by a conveyor (115) through a water trap (116) and eventually to the chamber (100). The cut feed material is moved on the bed (119) by a conveying means (119a) through the decomposition chamber (100) where it is ignited by the burners (117) and decomposed in a controlled atmosphere void of excess oxygen and controlled with respect to analysis and temperature. The feed material generally is heated to a temperature from about 315-649 °C (600 to 1200 °F) for best decomposition.

The insulation on the feed material decomposes and burns in the decomposition chamber (100). The clean copper wire leaves the decomposition chamber (100) through an exit water seal (120) which also acts as a quench for the wire scrap, thereby cooling and further cleaning the product. The product from the water seal (120) is collected in a receptacle (121) or a bailer for further handling.

The gases and smoke generated during decomposition, which contained chlorine, pass into an afterburner (111) where all of the remaining combustible products are consumed.

The after burner includes a burner (122) and an excess combustion air inlet (123). The afterburner operates at a temperature of about 760-1093 °C (1400 to 2000 °F). The burner gases from the afterburner (111) still contain chlorine as well as the products of combustion's.

The products of combustion, including the chlorine from the afterburner (111), are passed through a fluidized bed reactor (112) where the fluidized bed material is a calcium-containing substance. The substance is calcium carbonate ($CaCO_3$).

The gases from the afterburner (111) act as the fluidizing medium. The intimate contact of the exhaust gases with the calcium carbonate causes a chemical reaction to take place in which the chlorine is reacted with the calcium carbonate to produce calcium chloride.

The calcium carbonate is deposited in a conveyor (124) where it is carried to a hopper (125) and then passed through a rotary air lock feeder (126) to the fluidized bed reactor (112).

The calcium carbonate passes across the bed in fluidized condition to the exit rotary air lock (127). The air lock feeder (126) controls feed of make-up calcium carbonate to the reactor (112) to replace that consumed in the reaction.

From the fluidized bed reactor (112) the gases, less the chlorine, are passed through the mechanical dust collector (113) and then exit through the induced draft fan (114) which provides the pressure differential to flow the gases through the entire system.

2.1.7 Care Car Concept

The Care Cars are a small fleet of experimental vehicles that are similar to Dodge Stratus sedans, but are very different from today's production Dodge Stratus. These automobiles have been designed with a 40% recycled content. These vehicles are Concepts for Advanced Recycling and Environmental Solutions (hence the name CARE). In comparison, the regular production vehicle has between 10% and 15% recycled content [22]. The two concept cars (each with different interiors) represent more than $3 million in contributions from sponsoring suppliers:

Figure 7 –Care Concept Vehicle (from [24])

To participate in the CARE project, suppliers had to meet one or more of three requirements: resin consolidation, 25% of more recycled content on the system's mass, and/or a design that effectively improves recyclability [22].

CARE pursues model year 2005 vehicle recoverability of 95% as outlined by DaimlerChrysler Characteristic Standard CS-90003D; this standard requests suppliers for information regarding the material they supply to DaimlerChrysler. Project CARE evolved in 8 months with suppliers working with DaimlerChrysler engineers and purchasing representatives. The cars now will undergo road simulation and proving ground testing in the coming months [22].

2.2 Background Research on Cryogenic Process

2.2.1 Introduction

The term Cryogenics, derived from the Greek word for icy cold, "Kryos," when combined with the suffix "genics," literally means "suitable for production by icy cold conditions [21]."

Low temperatures can be conveniently defined as those at which the so-called "permanent" gases, such as oxygen and nitrogen, become liquids at normal atmospheric pressure. Cryogenics, then, is the utilization of low temperature processes to produce physical changes in liquids, gases, or solids.

In the field of cryogenic engineering, one is concerned with developing and improving low-temperature techniques, processes, and equipment. The field of cryogenics involves temperatures below -150°C (-240°F or 220°R). This is a logical dividing line, since the normal boiling points of the so-called permanent gases, such as helium, hydrogen, neon, nitrogen, oxygen, and air, all lie below -150°C (-240° F). Present day applications of cryogenic technology are widely varied, both in scope and in Magnitude [20].

2.2.2 Liquid Nitrogen

Liquid nitrogen will be used in the testing chamber, which will be discussed further in the paper. Liquid nitrogen is a clear, colourless fluid, which resembles water in appearance. At 1 atm pressure liquid nitrogen boils at -195.75°C (77.4K) and freezes at -209.95 °C (63.2°K). Its value to the cryogenic engineer is considerable for it is neither explosive nor toxic and, unlike oxygen, it is quite inert [20].

Table 2 below shows some important physical characteristics of common liquefied gases. The physical characteristics of liquid nitrogen are provided in this table.

Refrigerant	Water	Liquid oxygen	Liquid nitrogen	Liquid hydrogen	Liquid helium
Boiling point (K)	373·2	90·2	77·3	20·4	4·2
Freezing point (K)	273·2	54·4	63·2	14·0	–
Density ($g\ cm^{-3}$)	1·00	1·14	0·80	0·07	0·13
Latent heat of vaporization ($J\ cm^{-3}$)	2258	243	161	13·6	2·7

Table 2-Fluid Properties (from [16])

Some important characteristics of common liquefied gases

The increasing importance of cryogenics in both industry and research has led, especially during the last decade, to extensive investigations of the physical properties of materials at low temperatures. These studies were initially confined to metals and alloys because of their use as structural materials, however, polymer metals have come under investigation because of their use in thermal insulation. The most noticeable change with metals as they are cooled is the increase in tensile and yield strengths, and although plastics show similar behavior they are likely to become brittle and may shatter if cooled too rapidly.

Polymers consist of long chains of molecules built up from relatively simple molecular units known as mers, hence the name "polymer". In thermosetting polymers, cross-linkage of chains occurs during curing, resulting in a strong though brittle material, and once cured further heating will not soften it. In the thermoplastic polymer, the chains are held together by weak bonds which, under stress, will permit movement of the molecular chains and heating will allow the material to be reshaped. Lowering the temperature brings out strengthening of the bonds and an increase in rigidity until, the polymer passes through the glass transition temperature. This is usually around 150 K, when it becomes completely brittle [16]. In Figure 8, you can see that most polymers when cooled to low temperatures show considerable increase in tensile strength.

Figure 8 – Tensile strengths of common automotive polymers at liquid helium, liquid nitrogen, and room temperatures (from [16])

This figure shows the tensile strengths of common automotive polymers at liquid helium, liquid nitrogen, and room temperatures. 1. Polytetrafluoroethylene (PTFE); 2. Polypropylene; 3. Polyethylene (low density); 4. Polyethylene (high density); 5. Nylon

When handling and storing liquid nitrogen, the same precautions should be observed as in handling liquid oxygen. The gaseous nitrogen is neither toxic nor explosive, so there are no special instructions to be followed other than those observed for compressed air. A small quantity of liquid left in an uninsulated vessel will pressurize the vessel upon evaporation. The final pressure is dependent on the volume of the vessel and the quantity of liquid inside.

The high-performance storage vessels in use today are based on the concept of the Dewar design, which is a double-walled container with the gas-evacuated space between the two walls filled with insulation. The Dewar vessel is normally the basis for cryogenic-fluid vessel design.

The storage vessel consists of an inner vessel called the product container, which encloses the cryogenic fluid to be stored and is enclosed by an outer vessel or vacuum jacket, which contains the high vacuum necessary to enhance the effectiveness of the insulation and serve as a vapor barrier to prevent migration of water vapor or air.

2.3 Background Research On Copper

2.3.1 Introduction

Copper and copper alloys have been recycled for hundreds of years. If newly mined ore was not available, copper objects could be melted and cast into new objects. During the war, weapons were made from recycled decorative and household goods, and including bells. After the war, they were turned back into non-military related products.

For nearly 5,000 years, copper was the only metal known to man. Today, it is one of the most used and reused of our "modern" metals [17].

2.3.2 Recovery Processes

Today, the process of transforming unalloyed copper scrap into new copper products begins with purchasing copper scrap from a national network of scrap processors and brokers. Scrap is classified as: No. 1 scrap which consists of clean, unalloyed, and uncoated copper solids, clippings, punchings, bus bars, commutator segments, clean pipe and tubing. No.2 copper scrap (which is the same as No. 1) but may include oxidized or coated/plated pieces including oxidized of coated copper wire free of excessive oxidation [17].

When copper scrap is received for recycling it is visually inspected and graded, and analyzed chemically. Loose scrap is baled and stored until needed. No. 1 scrap material is directly melted and in some cases brought to higher purity while molten (fire refined). Chemical analysis checks the purity of the copper when the furnace charge is fully melted, and the molten copper is deoxidized to obtain the desired purity level. The first scrap anodes are the raw material used in cathode production.

Since usable energy is to become more scarce and therefore more expensive, it will play a more dominant role in determining the place of recycling in society. The evaluation of the total energy expenditures in the production and recycle of important structural metals, has been summarized in Table 3. This table expresses the relative energy requirements of recycling and extraction from present and future primary ores. These figures show that in all cases there are significant energy savings in recycling. Energy required for sorting or separating the scrap from mixed waste streams is not included in Table 3, but this would only add about 10% to the recycle energy [17].

Metal	Source	Recycle energy/Production energy (%)
magnesium	sea-water	1.5
aluminum	50% bauxite	2.5-3.9
	(30% bauxite)	2.2-3.4
	(clays)	2.0-3.0
	(anorthosite)	1.8-2.8
iron	high-grade hematite	29
	magnetic taconite	27
	(specular hematite)	24
	(nonmagnetic taconites)	24
	(iron laterites)	20
copper	1% sulfide ore/98% scrap	4.7
	1% sulfide ore/impure scrap	11.5
	(0.3% sulfide ore/98% scrap)	2.6
	(0.3% sulfide/impure scrap)	6.2
titanium	high-grade rutile ore	31
	ilmenite rocks	26
	ilmenite beach sands	26
	ferruginous rocks	26
	(high titania clays)	25
	(high titania soils)	19

Table 3- Relative Energy Requirements of Recycling and Production from Ores for Several Metals (from [18])

This figure shows the relative energy requirements of recycling and production from ores for several metals, with possible future ores in parentheses.

As the proportion of material recycled increases beyond a certain point, the cost of separation increases rapidly, and for any material under any particular set of conditions, there exists a point at which the energy expenditures on recycling equals the energy required to extract it from "natural" ores. This has been illustrated for copper in Figure 9. The minimum of the "total" curve occurs at about 60% recovery [18].

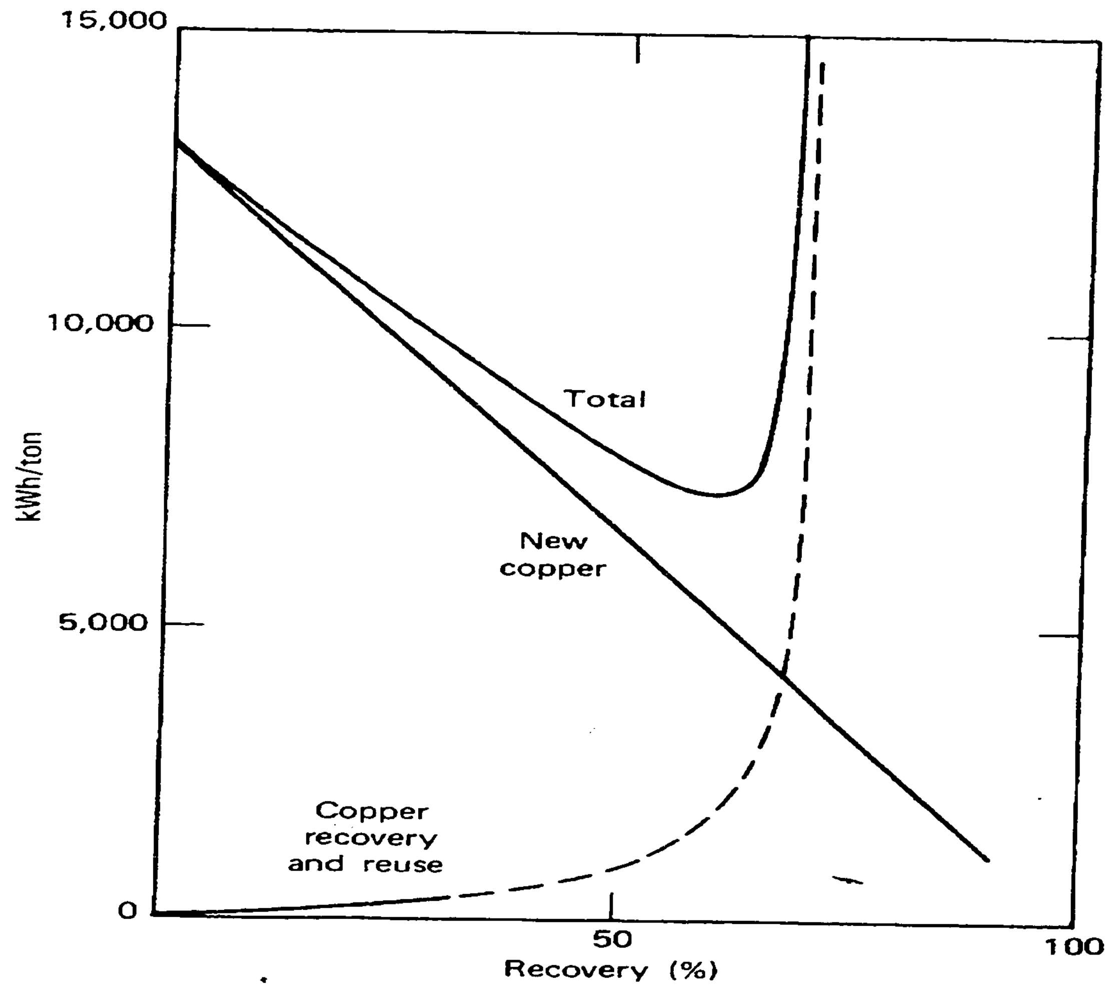


Figure 9- Optimization of energy consumption for the recycling of copper. (from [18])

This figure shows that as the proportion of material recycled increases beyond a certain point, the cost of separation increases rapidly, and for any material under any particular set of conditions, there exists a point at which the energy expenditures on recycling equals the energy required to extract it from "natural" ores. This has been illustrated for copper in the figure above. The minimum in the "total" curve occurs at about 60% recovery.

2.3.3 Copper Wires

All electrical wires and cables are not created equal. Stretching over thousands and thousands of kilometers, the reliability of an entire system comes down to dependability of each and every wire. The very first harness in a car was 1.5m long, running from the engine to the instrument panel to enable the engine to be stopped from the driving position by shorting the ignition. Since that time, wiring harnesses have grown in size and weight [17].

Helical extrusion is being specifically developed for the manufacture of copper wire. Helical extrusion is a combination of three forming stages, know as hydrostatic extrusion, conventional extrusion, and an intermediate stage which has similarities to the lathe turning process. Because all three take place simultaneously, helical extrusion is a single operation which reduces billets directly to wire.

A billet, preferably of circular section, is extruded through a conical die and over the conical tip of a piercing mandrel, producing a cross-section of annular form which is depicted in Stage 1 of Figure 10. As the annulus forms, a strip of billet material is circumferentially collected from it by a tool rotating in the plane of the annulus, which is shown in Stage 2 of Figure 10. In Stage 3, the stripped material is extruded through a die hole situated immediately in front of the collecting tool and rotating with it. Figure 11 shows that Stages 2 and 3 occur simultaneously, and that no strip of material is produced [17].

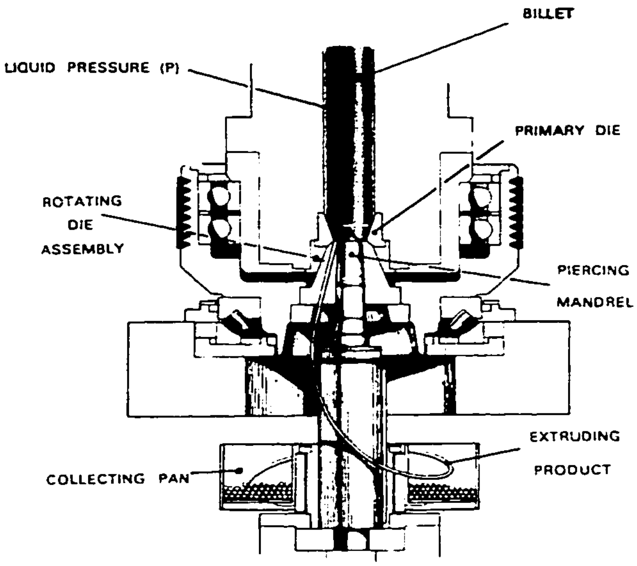


Figure 10- Helical Extrusion. (from [17])

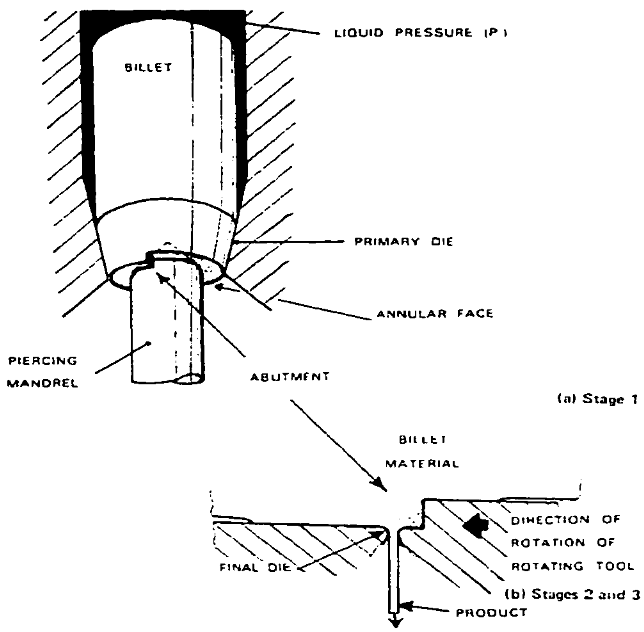


Figure 11- Helical Extrusion. (from [17])

2.4 Background Research On Higher Voltages – 42 Volts

The increasing consumer demand for new power functions is driving the need for efficient, high voltage distribution system in vehicles. The dual voltage architecture maintains the current 12-volt power needed for loads such as the vehicle's incandescent lamps and small power motors and actuators, while deploying the 42-volt power bus for the new, high power demanding loads such as electromagnetic valves and electrically heated catalytic converters. The introduction of the two voltage systems increases the efficiency of the whole electronic and electronic distribution system, and optimizes size, weight and cost. The use of the 42 volt system would allow for a higher voltage resulting in a lower current which would allow for smaller conductors resulting to better packaging conditions.

3 Development of Test Methodology

3.1 Recycling Concept

While in most cases copper is recovered from electrical scrap by chemical treatment or by destroying the insulation (e.g., by burning it off), it may be possible to recover both the base copper and the insulation in a mechanical separation process. This paper discusses a unique process for the recycling of complex automobile parts, such as wiring harnesses. This process is one utilizing cryogenic means for separating metallic conductor wire from its insulation for reclamation of the metal and potentially the insulation material.

The proposed process will be developed to recover the copper found in automotive wiring harnesses. The first step requires removing the wiring harness from the engine compartment, the interior compartment, or the dashboard of a vehicle. The next step will require investing the materials of the harness to provide information regarding the low temperature characteristics of all of the materials in the harness. When all materials have been distinguished, the wiring harness will be stripped of all connectors, leaving only the wire and the insulation material.

A mechanical system has been designed where random size, non uniform masses of insulated wire will be soaked in liquid nitrogen, and then it will be taken through a process which will shatter the insulating material from the wire. Experiments will be performed to determine the optimum time and temperature to provide the highest amount of recovered copper.

The wiring harness used for testing has been taken from a 1998 Plymouth Breeze (2.0L engine).

Table 4 shows that most of the wiring harness properties are able to withstand up to the temperature of –40 °C before they actually begin to fail or pass into the glass region. This means that if the wiring harness is exposed to liquid nitrogen the temperature of these materials will fall much lower than that of –40 °C. Therefore theoretically one can assume that the insulation will become brittle and failure will occur once the harness has been subjected to these environmental conditions.

Material Properties of Wiring Harness Assemblies

WIRE	PROPERTIES	TEMPERATURE RANGE
Cable-Primary Heavy Duty Hypalon Insulated	Copper Conductor	121°C (250°F) to -40°C (-40°F+/-3°F)
Cable-Primary Thin Wall Cross Linked Polyethylene Insulated	Copper Conductor	150°C (302°F) to -40°C (-40°F+/-3°F)
Cable-Primary Heavy Wall Cross-Linked Polyethylene Insulated	Copper Conductor	150°C (302°F) to -40°C (-40°F+/-3°F)
Cable-Primary Standard Wall Thermoplastic (PVC) Insulated	Copper Conductor	121°C (250°F) to -40°C (-40°F+/-3°F)
Cable-Primary Heavy Duty Hypalon Insulated	Copper Conductor	122°C (252°F) to -40°C (-40°F)
Cable-Primary High Temperature Thin Wall Cross Linked Polyethylene	Copper Conductor	150°C (302°F) to -40°C (-40°F+/-3°F)
Cable-Primary Heat Resistant (PVC) Insulated	Copper Conductor	142°C (287°F) to -40°C (-40°F+/-3°F)
Cable-Primary Thin Walled Thermoplastic (PVC) Insulated	Copper Conductor	121°C (250°F) to -40°C (-40°F+/-3°F)
Cable-Primary Standard Wall Cross-Linked Polyethylene Insulated	Copper Conductor	150°C (302°F) to -40°C (-40°F+/-3°F)

TAPE	TEMPERATURE RANGE
Tape-Cotton Backed Friction Pressure Sensitive Electrical Application	70°C (158°F) to 26°C (78°F)
Tape-Electrical Harness High Temperature Resistant	149°C (300°F) to 22°C (72°F)
Tape-Wiring Electrical Insulation	79°C (158°F) to -29°C (-20°F)
Tape-Flame Retardant Polymetric Coated Cloth Pressure Sensitive Electrical Applications	70°C (158°F) to 26°C (78°F)
Tape-Paper Backing Pressure Sensitive Type	79°C (175°F) to -29°C (-20°F)
Tape-Coated Cotton Water Resistant	70°C (158°F)
Cable-Primary Heat Resistant (PVC) Insulated	142°C (287°F) to -40°C (-40°F+/-3°F)
Tape Black Crepe Paper Backing Pressure Sensitive	93°C (200°F) to 22°C (72°F)
Tape-Flame Retardant Polymetric Sleeve Pressure Sensitive Electrical Applications	105°C (221°F) to -29°C (-20°F)

TUBING	TEMPERATURE RANGE
Thermoplastic-Polyolefin Heat Shrinkable Tubing	225°C (437°F) to -40°C (-40°F)

SLEEVE	TEMPERATURE RANGE
Thermal Insulation Fiberglass-Braided And Treated Tubing	371°C (700°F)
Sleeve Braided Fiber Glass Normalized and Treated Non Fraying	500°C (932°F) to -60°C (-76°F)

Table 4- Wiring Harness Temperature Properties (from [15])

These are the maximum temperatures that the harness components have been tested to, in order to avoid failure.

3.2 Testing Apparatus

The author has designed a test apparatus, consisting of a holding chamber or stand, which will allow liquid nitrogen to be put in contact with the wiring harness. This system will allow the wiring harness to be soaked for a specific amount of time and allow the experimenter to determine what exposure time produces the most favorable results. A set of rollers has been designed by the author, through which the harness will pass, in order to shatter the insulation, leaving only a bare copper wire. This prototype system will allow for the potential future development of a larger commercial system, which would provide an efficient method of recovering copper from all the wiring harnesses found in an automobile.

3.3 Material Selection

The liquid nitrogen soaking system will use a PGS 60 low pressure cryogenic container that is able to hold 128 m^3 of liquid nitrogen. This device is shown in Figure 12.

Figure 12-Cryogenic Vessels

This tank is equipped with cryogenic regulators to resist freeze-up, the economizer valve stops exhaust of useful product and an alarm activates lights to announce changeover and controls optional remote alarms. It is a low pressure vessel (60 PSI).

The process will allow the liquid nitrogen to flow from the low pressure cylinder into a stainless steel bath, by the means of a transfer hose as shown in Figure 13. In order to have the cryogenic hose adapt to the chamber, certain fittings were used. These are shown in Figure 14.

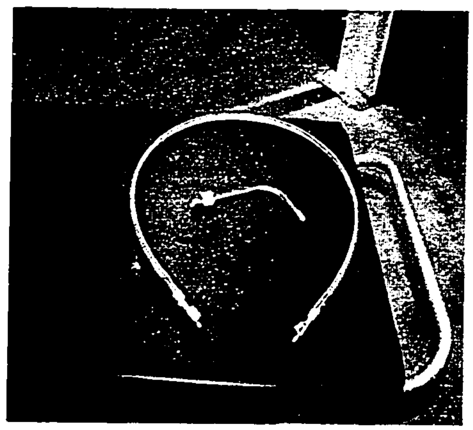


Figure 13- Cryogenic Transfer Hose

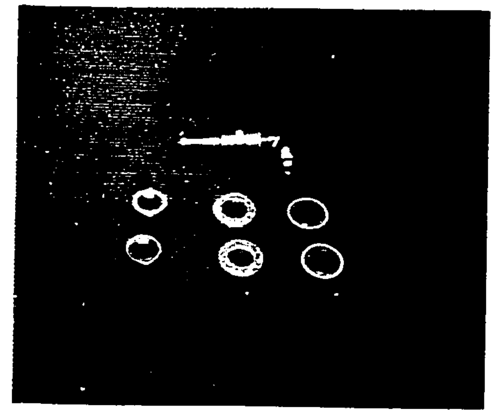


Figure 14- Cryogenic Fittings

This stainless steel pan will be large enough to hold the stripped wiring harnesses. The tub will be manipulated to allow the flow of liquid nitrogen into the tub. Once the tub has been loaded with the harnesses a flow of liquid nitrogen will be used to saturate them until their insulation becomes brittle enough to remove. An investigation into the elapsed time which the harness remains in the tub and the ease of removing the insulation will be conducted. If the insulation is difficult to remove, then the harness will be kept in the bath for a longer period of time. The bath is a stainless steel cooking pan, which will be modified to withstand liquid nitrogen by having a layer of foam insulation installed on the outside and placing it in a holding chamber in order to limit the amount of evaporation of the liquid nitrogen. The insulation will be 25 mm (1inch) thick, and will cover the stainless steel pan. This is shown in Figure 15, 16, 17 and 18.

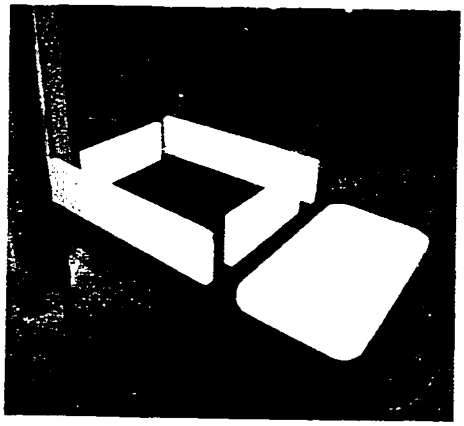


Figure 15-Foam Insulation

Figure 16- Stainless Steel Tub

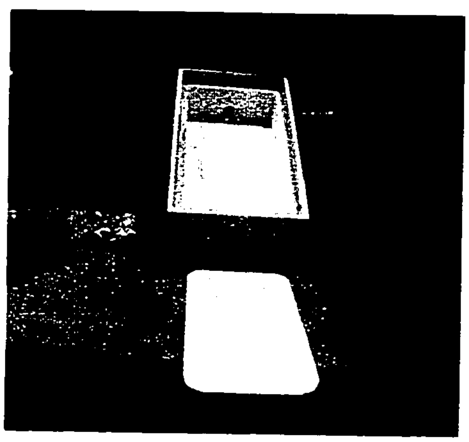


Figure 17-Plywood Casing with Foam

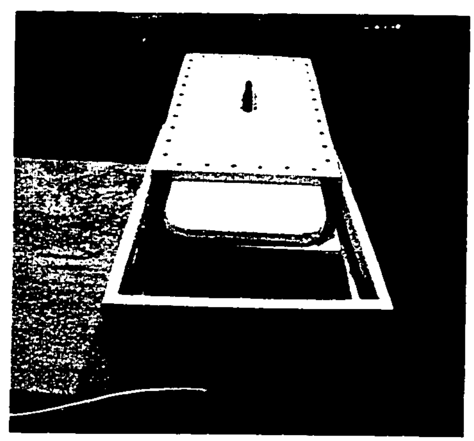


Figure 18-Proposed Complete System

The design of a mechanical roller system is illustrated below in Figures 19, 20 and 21. The roller system was designed at the ARDC. The system consists of two metal plates, one of size 406mm x 304 mm (16 inches by 12 inches), which holds a small timing sprocket (taken from an engine crankshaft) and the other plate of size 114 mm X 190 mm (4.5 inches by 7.5 inches), which holds a large timing sprocket (taken from a camshaft).

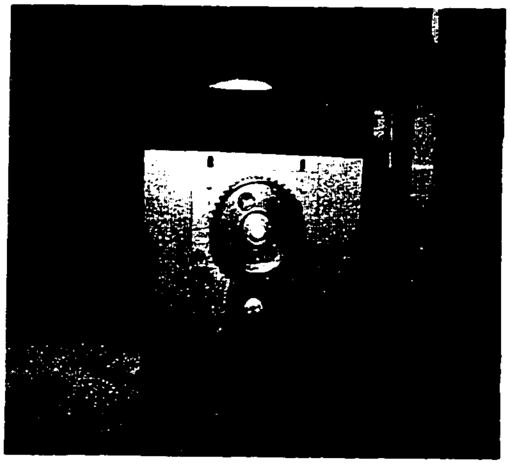


Figure 19-Roller System

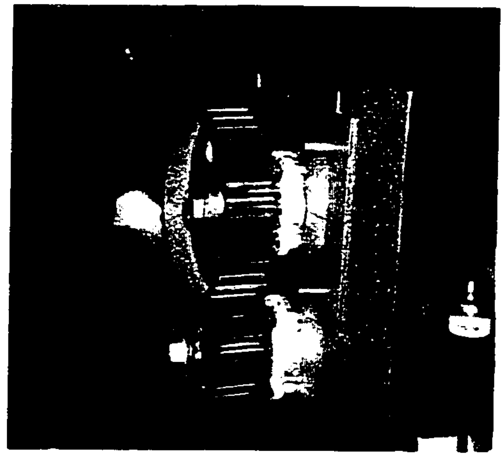


Figure 20-Adjustable Sprocket

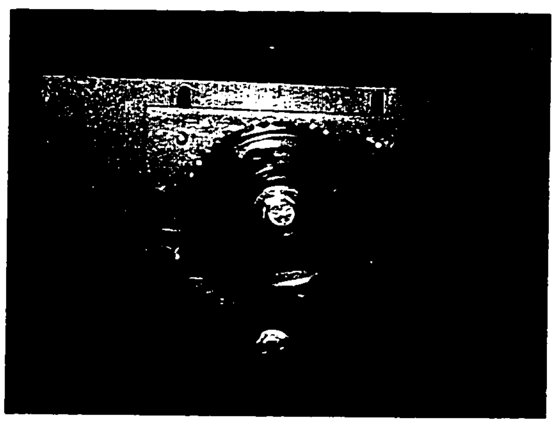


Figure 21- Mechanical Rolling System

The larger plate has slots cut into it, to allow the adjustment of the smaller plate to reduce or increase the amount of clearance between the two sprockets, this is shown in Figure 22 and 23. The adjustment of the plate is done by unscrewing four knobs located on the rear of the larger plate, this is shown in Figure 24.

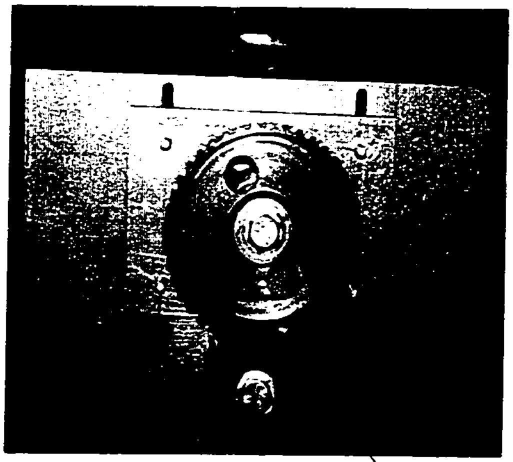


Figure 22-Adjustable Sprocket (small Clearance)

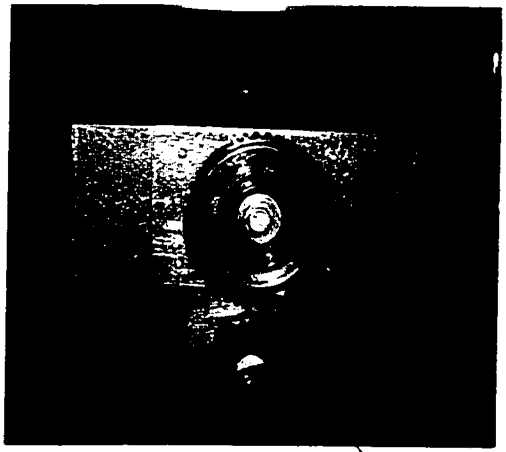


Figure 23-Adjustable Sprocket (large clearance)

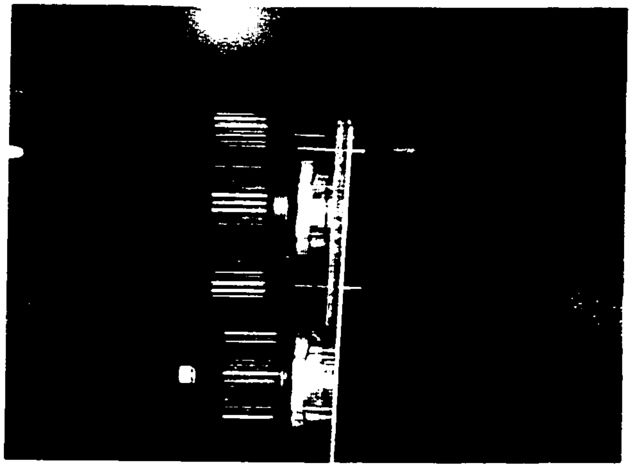


Figure 24 – Four Adjustable Knobs

Since there is a variety of wiring harness sizes, the bearings will have to be adjusted to crush and shatter the insulation from the harness leaving the copper wire. The bearings were attached to the plate with two bearing retainers that were taken from the alternator of an automobile. This is shown in Figures 25 and 26 below.

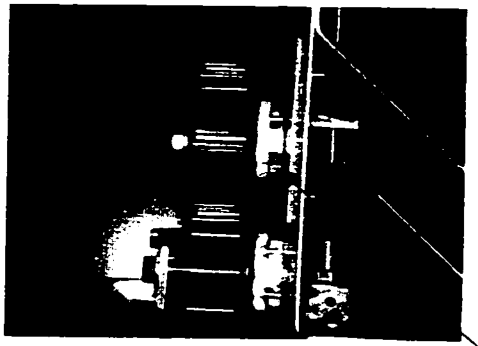


Figure 25 – Roller System-Bearing Retainers

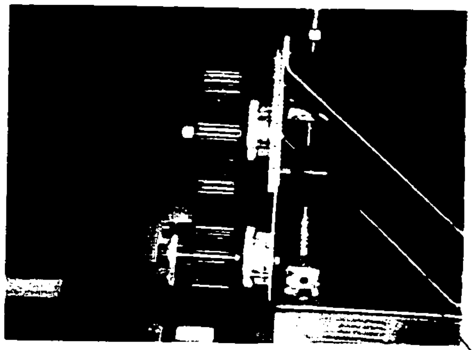


Figure 26-Roller System-Adjusting Knobs

A steel handle with a wooden hand grip has been attached to the smaller bearing to allow the user to rotate the crank gear in order to feed the wiring harness through it. The handle allows the user to rotate the gear at varying speeds. This is shown in Figure 27.

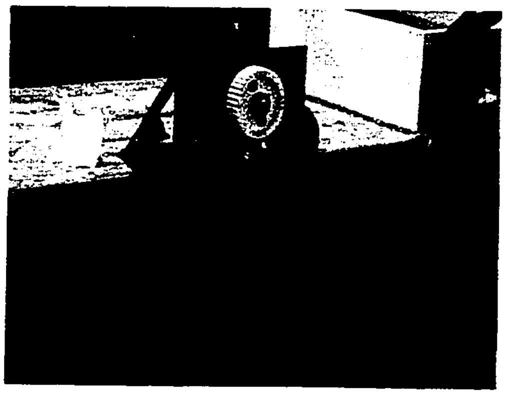


Figure 27 –Complete Assembly of the Roller System

The liquid nitrogen vessel will be coupled to the stainless steel bath by means of a transfer hose. Tongs will be used to insert and remove the wiring harnesses from the cooling chamber. Once the wires are frozen, they will be removed and placed in the rolling device. A collection bin will be placed underneath the rolling device to collect the shattered insulation for weighing.

3.4 Types of Tests

To ensure that data would be properly attained during experimental testing, two tests were performed. Test A (Complete Wiring Harness Test) required that the harness be soaked in liquid nitrogen without the removal of any material or components from the assembly. Test B (Wiring Harness Material Test) required the removal of all the different types of material found on a wiring harness and each material was tested individually in liquid nitrogen. A discussion of the basic steps taken for the procedure of these two tests, will follow.

3.5 Testing Procedure

3.5.1 Complete Wiring Harness Test

The complete harness test requires the testing of the entire harness without the removal of any components.

The first step is to take all the necessary safety precautions by making sure to wear the proper safety equipment. Eyes and hands must be protected at all times. Figure 28 shows the necessary safety equipment needed.

Figure 28-Safety Equipment Required

It is necessary to wear a jacket, gloves and protective face shield to avoid being splashed with liquid nitrogen.

Step 2 requires making sure that the cryogenic hose is safely fastened to the tank and the tub. This is checked to make sure there are no leaks or accidents. The system is shown in Figure 29. Then the tank is turned on and liquid nitrogen is allowed to flow from the tank to the tub. This is shown in Figures 30 and 31.

Figure 29-Cryogenic Tank

Figure 30 – On/Off knob for Liquid Nitrogen

Figure 31- Testing Cryogenic System

Step 3 requires checking the temperature of the bath using a thermometer to make sure that the tub is at a reasonably constant temperature. This is shown in Figure 32.

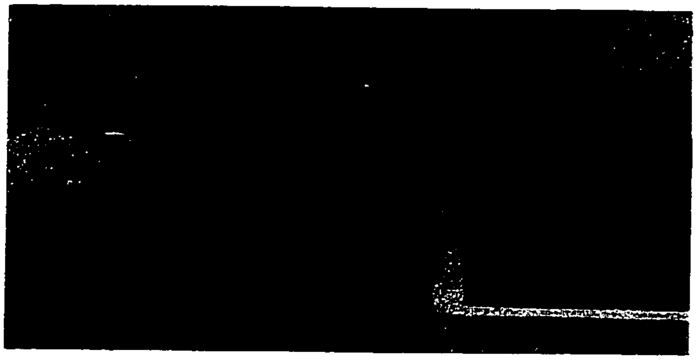


Figure 32- Checking Temperature of Liquid Nitrogen Bath

Step 4 is to load the complete harness into the tub and record the exposure time. This is shown in Figures 33 and 34.

Figure 33-Inserting Harness into Liquid Nitrogen

Figure 34-Processing Harness in Nitrogen

The final step, Step 5 is to take the frozen wiring harness and send it through the crusher to recover the copper. Figure 35 and 36 show this.

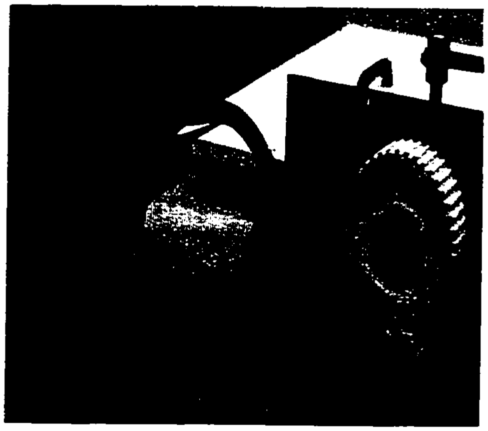


Figure 35- Removal of frozen harness

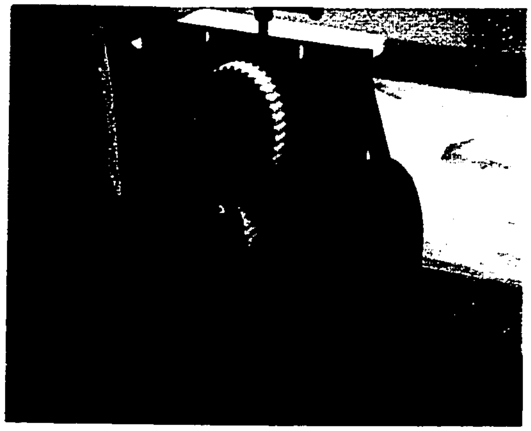


Figure 36-Crushing Frozen Wiring Harness

3.5.2 Wiring Harness Material Test

The Wiring Harness Material Test requires the removal of all the different types of materials found on a wiring harness.

Steps 1, 2 and 3 are similar to those for the Complete Wiring Harness Test.

Step 4 is to take each individual material and soak it in the liquid nitrogen.

Step 5 requires recording the amount of time it takes for the material to reach its glass transition temperature.

Step 6 requires taking the frozen material and sending it through the crusher to see which material can be easily shattered quickly.

4 Discussion of Experimental Results

The results from the test are described below in detail. The results were very promising many materials were able to reach there glass transition temperature. The materials which showed difficulty in reaching or obtaining there glass transition temperature are to be removed prior to being processed with liquid nitrogen.

4.1 Test A – Complete Wiring Harness Test Results

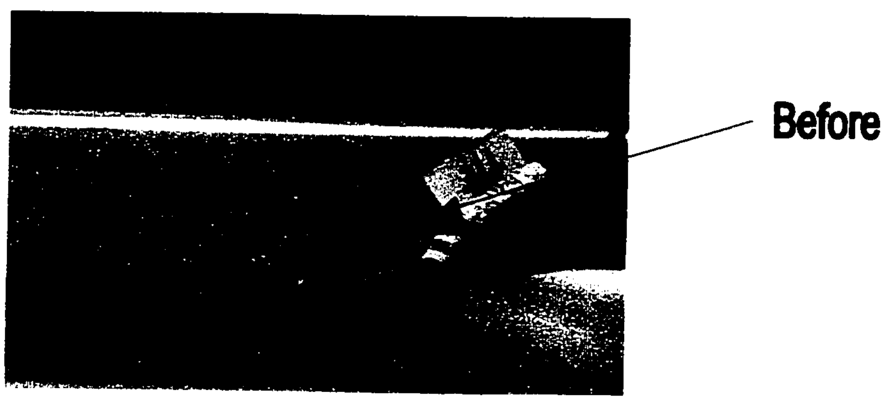


Figure 37-Complete Wiring Harness (Before Soaking in Liquid Nitrogen)

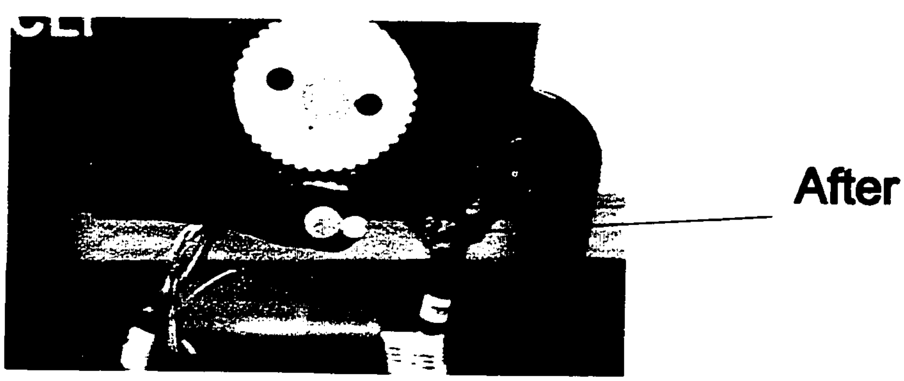


Figure 38- Complete Wiring Harness (After Soaking in Liquid Nitrogen)

This test did not provide favorable results, due to the fact that wiring harnesses have such a variety of different materials. It was very difficult to have all the materials reach their glass transition temperature at the same time. It was also very difficult to process the complete wiring harness through the crusher system. Test A was stopped, and Test B was conducted so that data could be obtained on which materials were able to reach their glass transition temperature and how long it took for them to achieve this state.

Complete Wiring Harness Test

2 min.	minor shattering, only 2% of material shattered		minor shattering, only 2% of material shattered
5 min.		minor shattering, only 2% of material shattered	
15 min.			
20 min.		very difficult to process, minor shattering	
25 min.			
45 min.	very difficult to process, minor shattering		very difficult to process, minor shattering
60 min.			
1 hr 30 min.	only 10% of material shattered	only 10% of material shattered	only 10% of material shattered

Table 5- Results of Complete Wiring Harness Test

4.2 Test B - Wiring Harness Material Test Results

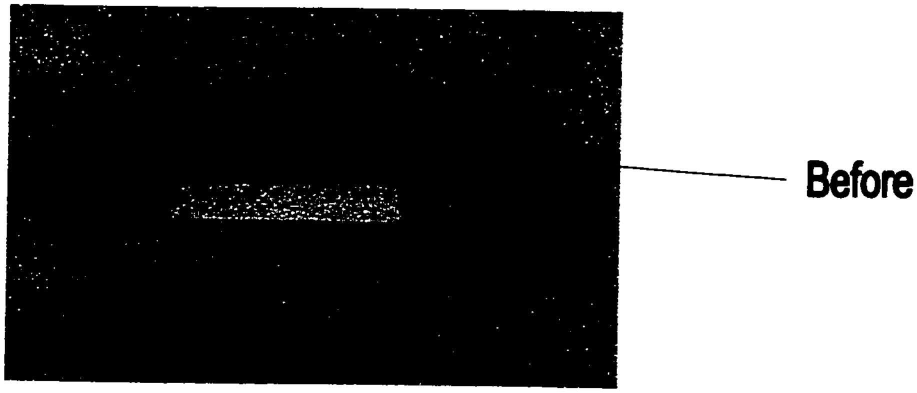


Figure 39-Thermoplastic-Polyolefin Heat Shrinkable Tubing (Before Soaking in Liquid Nitrogen)

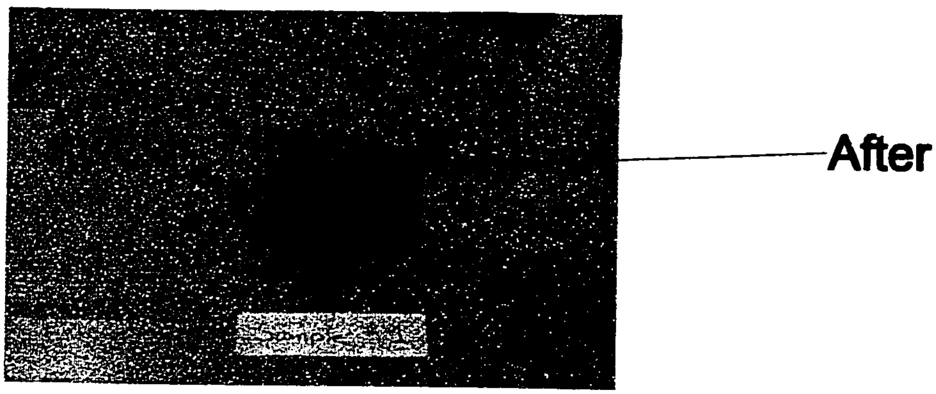


Figure 40- Thermoplastic-Polyolefin Heat Shrinkable Tubing (After Soaking in Liquid Nitrogen)

Sample #1- Thermoplastic-Polyolefin Heat Shrinkable Tubing

This material proved to have the most favorable results in the least amount of time. Thermoplastic – Polyolefin Heat Shrinkable Tubing reached its glass transition temperature in approximately 2 minutes. The test was repeated 3 times to guarantee that the results obtained were indeed accurate. In this case all three tests produced the same results.

Sample # 1- Thermoplastic-Polyolefin Heat Shrinkable Tubing

2 min.				crushed
5 min.		crushed	crushed	
15 min.				
20 min.				
25 min.				
45 min.				
60 min.				
1 hr 30 min.				

Table 6-Results of Wiring Harness Material Test for Thermoplastic Polyolefin Tubing

Figure 41-Cable-Primary Standard Wall Thermoplastic(PVC) (Before Soaking in Liquid Nitrogen)

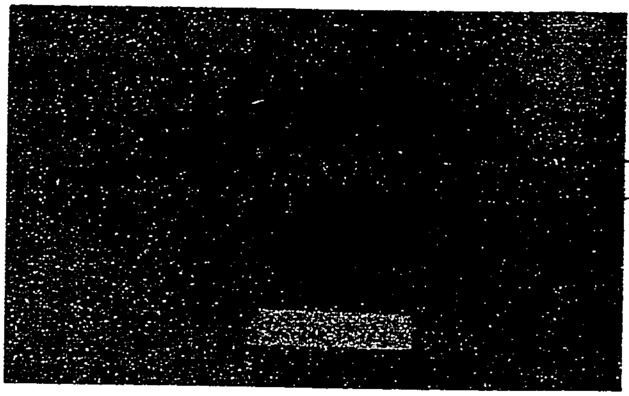


Figure 42-Cable Primary Standard Wall Thermoplastic (PVC) (After Soaking in Liquid Nitrogen)

Sample #2- Cable- Primary Standard Wall Thermoplastic (PVC)

This material is a low tension primary cable made with untinned stranded copper conductor and insulated with a thermoplastic insulation.

This material was taken out of the liquid nitrogen after 2 minutes and placed through the crusher system. Unfortunately it showed no apparent changes to the material, except for some minor cracks in the insulation. The material was then placed back into the bath for a longer period of time. It was then removed from the bath after 5 minutes, but it was observed that the (PVC) coating over the copper was still very difficult to remove. It was then placed back into the liquid nitrogen and removed after 25 minutes. The insulation began to crack but was not easily being removed to recover the copper. The cable was then left in the nitrogen for an hour and thirty minutes and the PVC insulation was crushed immediately leaving the bare copper wire. This test was repeated three times to guarantee accurate results were obtained.

Sample # 2- Cable- Primary Standard Wall Thermoplastic (PVC)

2 min.				cracks in insulation
5 min.		cracks in insulation		
15 min.			cracks in insulation	
20 min.		cracks in insulation		
25 min.			cracks in insulation	cracks in insulation
45 min.		cracks in insulation		
60 min.				
1 hr 30 min.		insulation shatters	insulation shatters	insulation shatters

Table 7-Cable-Primary Standard Wall Thermoplastic(PVC) Test Results

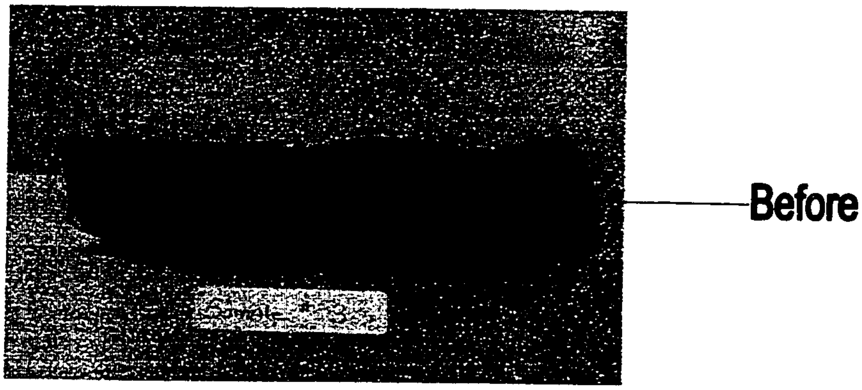


Figure 43-Nylon And/Or Polyester Abrasion Resistant Sleeves (Before Soaking in Liquid Nitrogen)

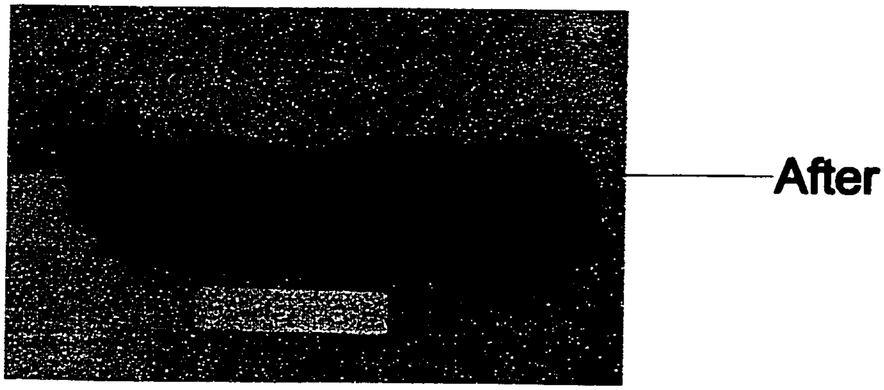


Figure 44- Nylon And/Or Polyester Abrasion Resistant Sleeves (After Soaking in Liquid Nitrogen)

Sample #3- Nylon And/ Or Polyester Abrasion Resistant Sleeves

This material is of polyamide (PA) and/or polyethylene terephthalate (PET) monofilament abrasion resistant sleeves.

This material showed no apparent material change when it was placed in liquid nitrogen. The Insulated fiberglass remained in the nitrogen for over 2 hours, and still showed no signs of being able to be crushed to small fragments. Therefore, from the data collected it can be concluded that the Nylon or Polyester Abrasion Resistant Sleeves show no change to material properties when placed in liquid nitrogen.

Sample # 3- Nylon and/or Polyester Abrasion Resistant Sleeve

2 min.		no change	no change	no change
5 min.				
15 min.				
20 min.		no change	no change	no change
25 min.				
45 min.				
60 min.				
1 hr 30 min.		no change	no change	no change

Table 8- Nylon And/Or Polyester Abrasion Resistant Sleeves Test Results

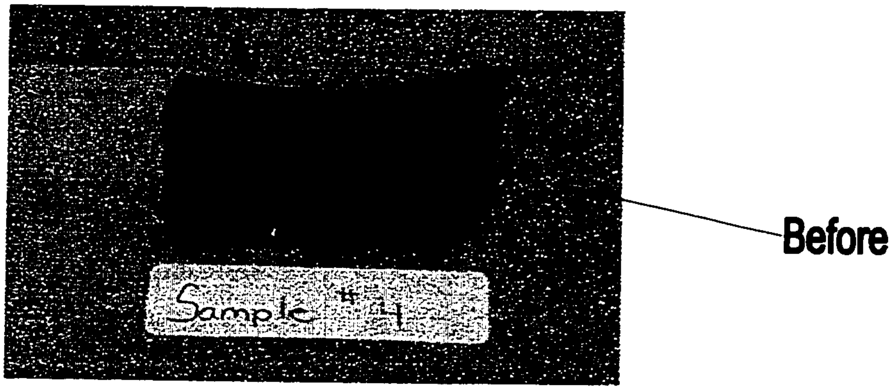


Figure 45-Reflective Sleeving-Woven Braided Fiberglass-(Before Soaking in Liquid Nitrogen)

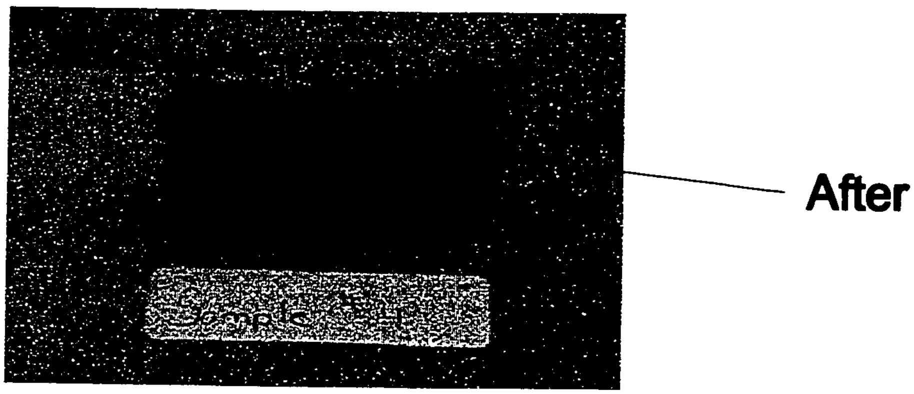


Figure 46- Reflective Sleeving-Woven Braided Fiberglass-(After Soaking in Liquid Nitrogen)

Sample #4 – Reflective Sleeving- Woven Braided Fiberglass- Bonded to Aluminum

This material defines the requirements for a braided or woven fiberglass fabric laminated to aluminum foil. This material is asbestos-free and is self-extinguishing without the use of flame retardant additives.

This material also showed no characteristics of being able to reach its glass transition temperature. It was placed in the liquid nitrogen bath for over two hours and the sleeving showed no material change.

Sample # 4- Reflective Sleeving- Woven Braided Fiberglass Bonded to Aluminum Foil

2 min.		no change	no change	no change
5 min.				
15 min.				
20 min.		no change	no change	no change
25 min.				
45 min.				
60 min.				
1 hr 30 min.		no change	no change	no change

Table 9- Reflective Sleeving-Woven Braided Fiberglass Test Results

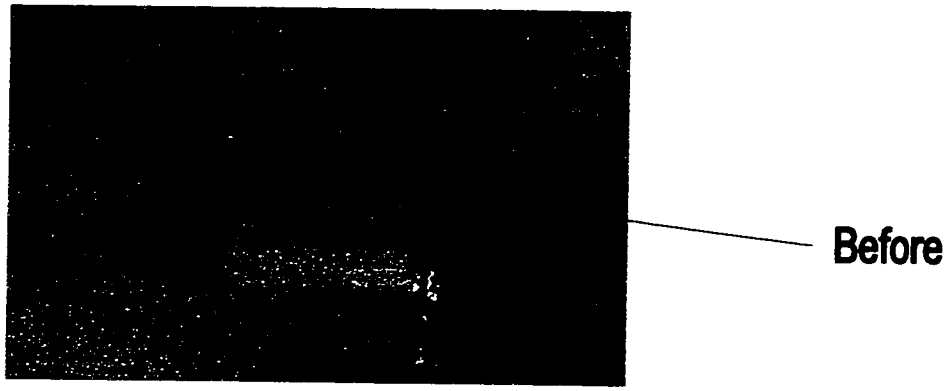


Figure 47-Heavy Duty Hypalon Insulated (Before Soaking in Liquid Nitrogen)

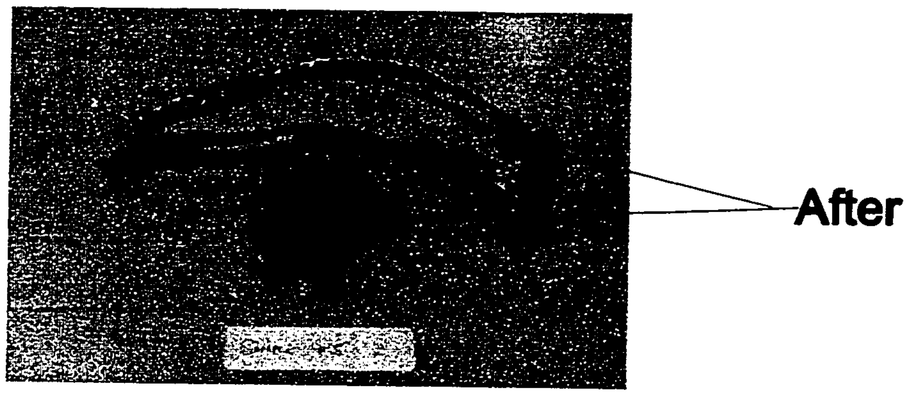


Figure 48- Heavy Duty Hypalon Insulated (After Soaking in Liquid Nitrogen)

Sample #5-Heavy Duty Hypalon-Insulated

This material covers a low tension primary cable made with stranded copper conductor and insulated with an engineering approved thermosetting insulation.

The insulation shattered off completely in 15 minutes leaving bare copper wire to be recycled. This shows results that can prove that it is possible to use liquid nitrogen to remove certain materials from automotive wiring harnesses. This test was repeated three times to guarantee accurate results.

Sample # 5-Cable Primary - Heavy Duty Hypalon- Insulated

2 min.		no change	no change	no change
5 min.		insulation cracks	insulation cracks	insulation cracks
15 min.		insulation shatters	insulation shatters	insulation shatters
20 min.				
25 min.				
45 min.				
60 min.				
1 hr 30 min.				

Table 10- Heavy Duty Hypalon Insulated Test Results

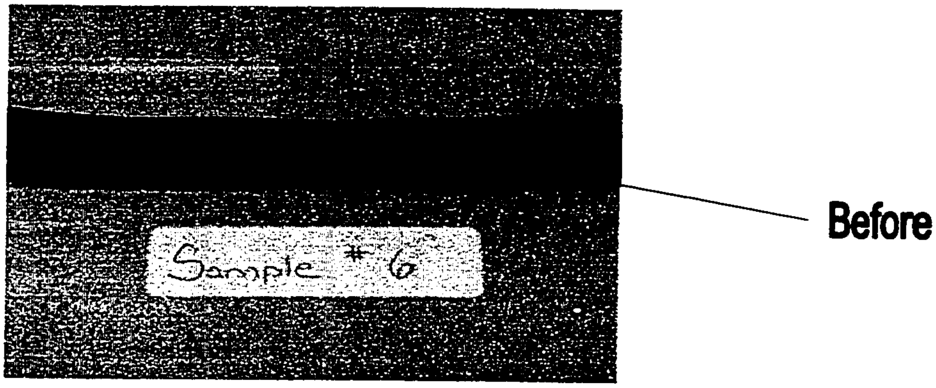


Figure 49-Sleeving Braided Fiberglass (Before Soaking in Liquid Nitrogen)

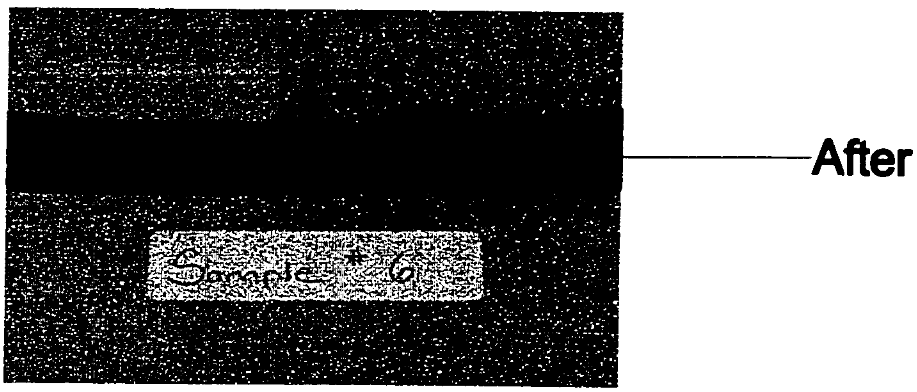


Figure 50- Sleeving Braided Fiberglass (After Soaking in Liquid Nitrogen)

Sample #6-Sleeving Braided Fiberglass

This material is an electrical grade of normalized and treated fiberglass sleeving. It is suitable for high temperature, low voltage applications. It is non-fraying, flexible and maintains its roundness thereby simplifying assembly.

This material remained in the liquid nitrogen bath for over two hours, and it was unable to reach it's glass transition temperature.

Sample # 6-Sleeving Braided Fiberglass

2 min.		no change	no change	no change
5 min.				
15 min.				
20 min.		no change	no change	no change
25 min.				
45 min.				
60 min.				
1 hr 30 min.		no change	no change	no change

Table 11- Sleeving Braided Fiberglass Test Results

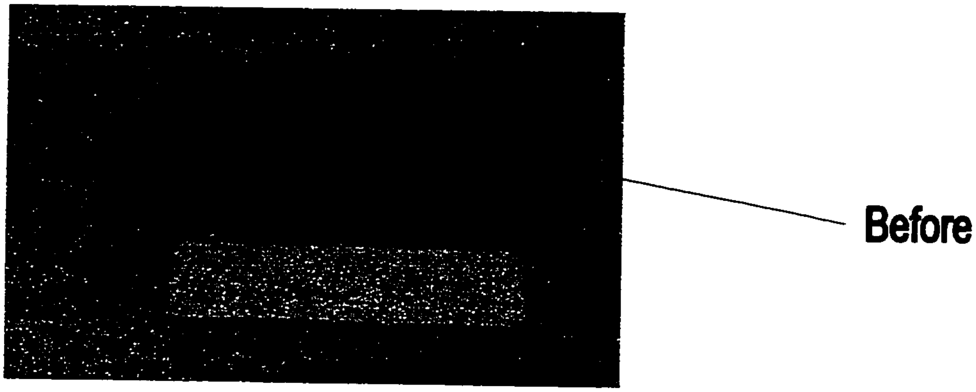


Figure 51-EPDM Bumper (Before Soaking in liquid Nitrogen)

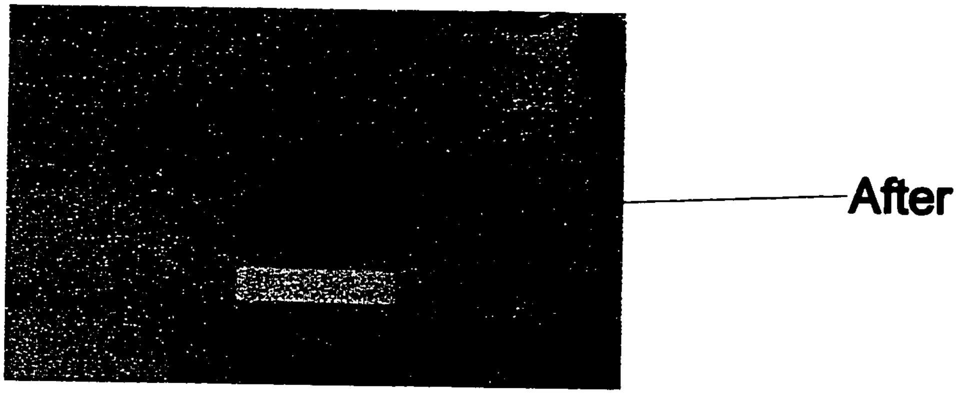


Figure 52-EPDM Bumper(After Soaking in Liquid Nitrogen)

Sample #7-EPDM Bumper

This material showed immediate result, the nitrogen immediately froze the bumper allowing it to be crushed into small fragments in less than 5 minutes.

Sample # 7- EPDM Rubber

2 min.		no change	shatters	no change
5 min.		shatters		shatters
15 min.				
20 min.				
25 min.				
45 min.				
60 min.				
1 hr 30 min.				

Table 12-EPDM Bumper Test Results

Figure 53-Tape-Polymeric Coat Cloth Pressure Sensitive (Before Soaking in Liquid Nitrogen)

Figure 54-Tape-Polymeric Coat Cloth Pressure Sensitive (After Soaking in Liquid Nitrogen)

Sample #8-Tape-Electrical Applications-Flame Retardant-Polymeric Coat Cloth Pressure Sensitive

This material presents requirements of a flame retardant fabric based tape with a polymeric protective coating on one side and a pressure sensitive adhesive on the other. The tape can be used for binding and protecting electrical connections, wiring harnesses, and cables.

This tape showed no change when brought in contact with the liquid nitrogen. It remained soaking in the liquid nitrogen for over two hours, but this material would not reach its glass transition temperature.

Sample#8-Tape-Flame Retardant-Polymeric Coated Cloth-Pressure Sensitive

2min		no change	no change	no change
5min				
15min				
20min		no change	no change	no change
25min				
45min				
60min				
1hr30min		no change	no change	no change

Table 13-Tape-Polymeric Coat Cloth Pressure Sensitive Test Results

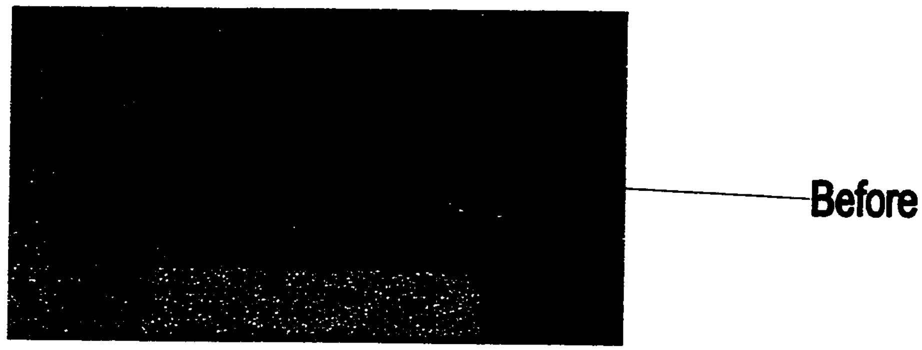


Figure 55-Tape-High Temperature Resistant (Before Soaking in Liquid Nitrogen)

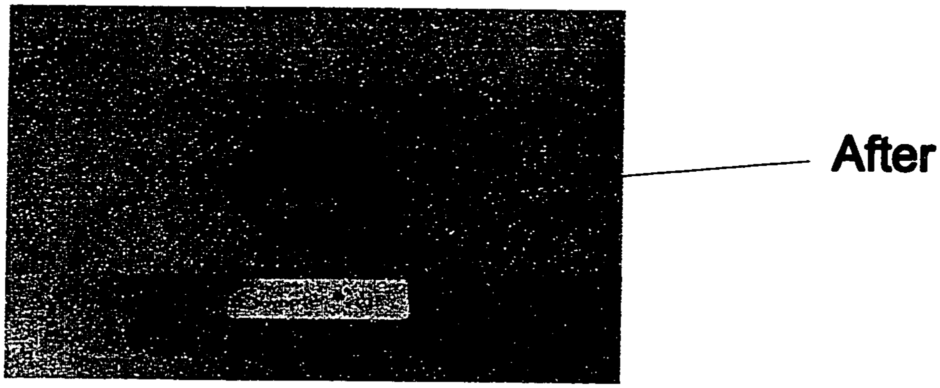


Figure 56-Tape-High Temperature Resistant (After Soaking in Liquid Nitrogen)

Sample #9-Tape Electrical Harness- High Temperature Resistant

This material presents the requirements for a glass cloth, high temperature resistant tape, having a heat curing, pressure-sensitive adhesive on one side. The tape is intended for binding and protecting electrical harnesses and cables in high temperature exposure areas.

This material reached its glass transition temperature close to 25 minutes when it was soaked in the liquid nitrogen. It was processed through the crusher system, reducing it down to small fragments.

Sample # 9- Tape Electric Harness

2 min.		no change	no change	no change
5 min.				
15 min.				
20 min.		no change	crushed	no change
25 min.		crushed		
45 min.				crushed
60 min.				
1 hr 30 min.				

Table 14-Tape-High pressure Resistant Test Results

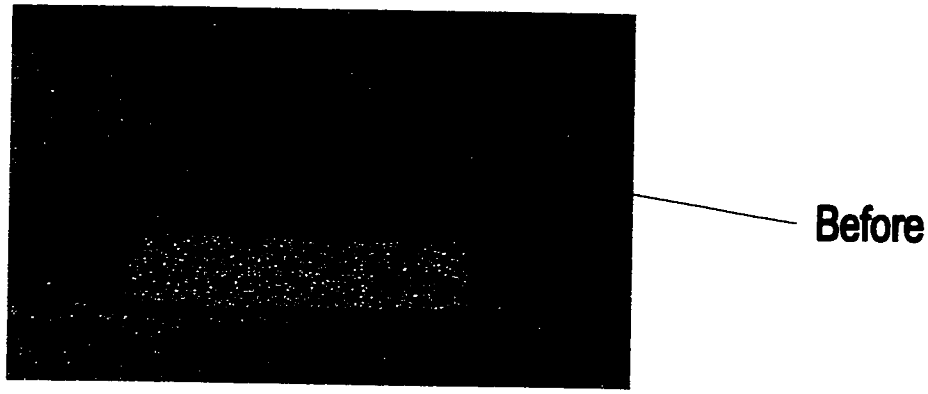


Figure 57-Tape-Paper Backing (Before Soaking in Liquid Nitrogen)

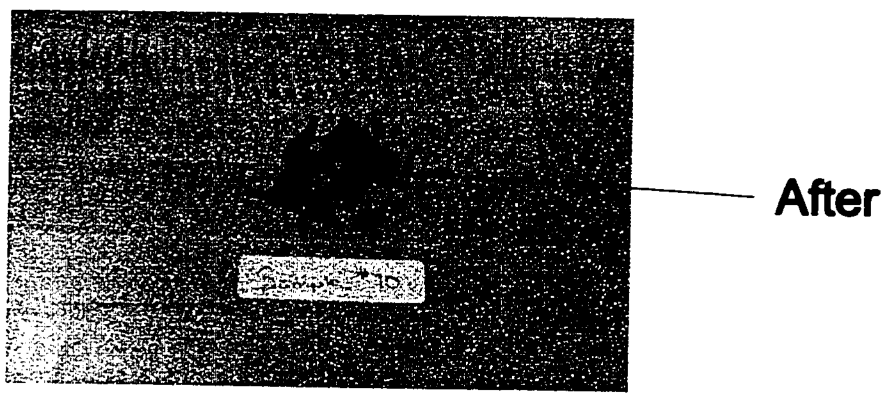


Figure 58-Tape-Paper Backing (After Soaking in Liquid Nitrogen)

Sample #10- Tape-Paper Backing- Pressure Sensitive

This material requires for a black, crepe paper backed, tape, having a rubber based, pressure sensitive adhesive on one side.

This material reached its glass transition temperature after being placed in liquid nitrogen for 15 minutes.

Sample # 10- Tape- Black Crepe Backing Pressure Sensitive

2 min.				
5 min.				
15 min.		crushed	crushed	crushed
20 min.				
25 min.				
45 min.				
60 min.				
1 hr 30 min.				

Table 15-Tape-Paper Backing Test Results

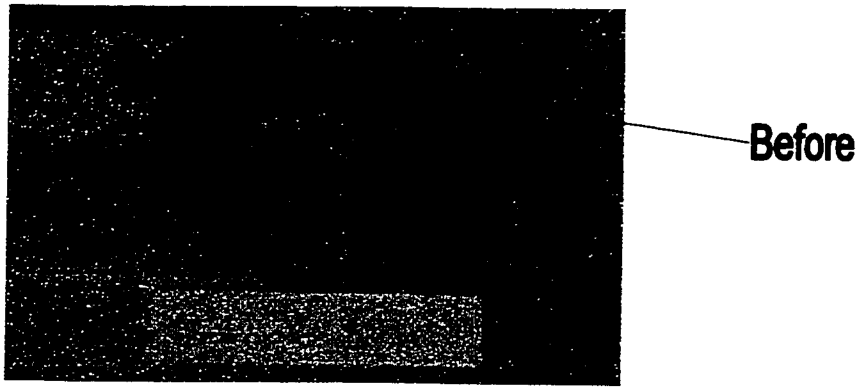


Figure 59-Cotton Backed Friction-Pressure Sensitive (Before Soaking in Liquid Nitrogen)

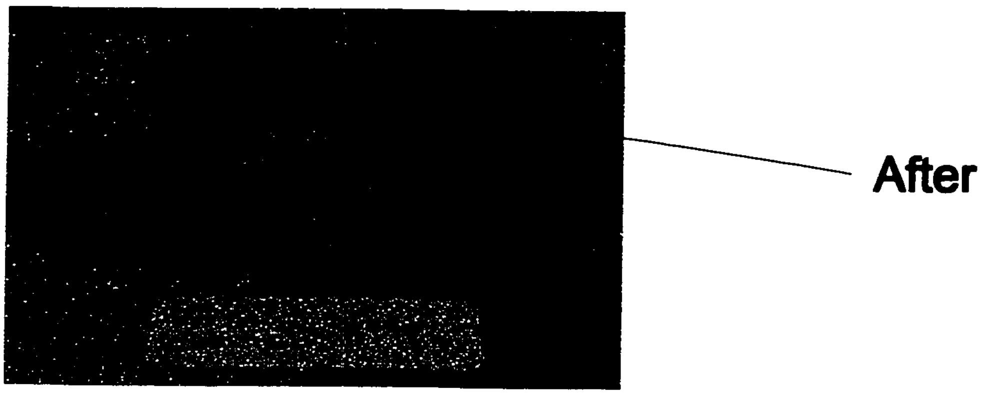


Figure 60-Cotton Backed Friction-Pressure Sensitive (After Soaking in Liquid Nitrogen)

Sample #11- Cotton Backed Friction- Pressure Sensitive- Electrical Applications

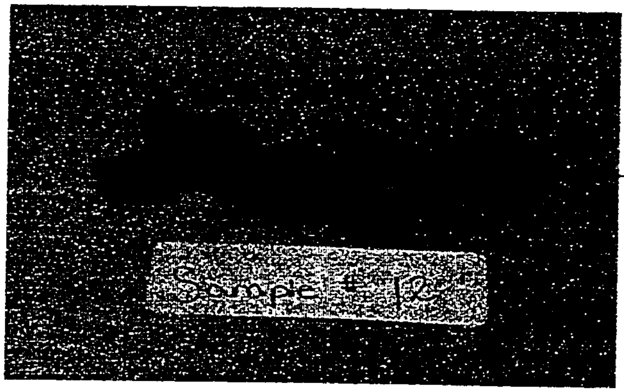
This material requires a black, cotton backed, pressure sensitive friction tape for binding and protecting electrical connections, wiring harnesses, and cables.

There was no change in the material when it was soaked in liquid nitrogen.

Sample # 11- Cotton Backed Friction - Pressure Sensitive

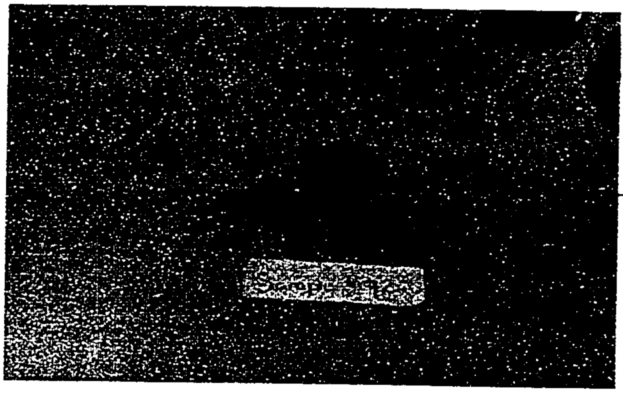
2 min.		no change	no change	no change
5 min.				
15 min.				
20 min.		no change	no change	no change
25 min.				
45 min.				
60 min.				
1 hr 30 min.		no change	no change	no change

Table 16-Cotton Backed Friction-Pressure Sensitive Test Results



Before

Figure 61-Tape-Water Resistant (Before Soaking in Liquid Nitrogen)



After

Figure 62-Tape-Water Resistant (After Soaking in Liquid Nitrogen)

Sample #12- Tape- Coated Cotton- Water Resistant

This material covers a grade of coated cotton tape treated to render it water resistant. It is recommended as a sealing tape on installations requiring a tape of low-permeability with good adhesion on to painted metal and to water resistant paper.

This material reached its glass transition temperature immediately. It only required being soaked in the liquid nitrogen for 5 minutes.

Sample # 12- Tape Coated Cotton- Water Resistant

2 min.		no change	no change	no change
5 min.		crushed	crushed	crushed
15 min.				
20 min.				
25 min.				
45 min.				
60 min.				
1 hr 30 min.				

Table 17-Tape-Water ResistantTest Results

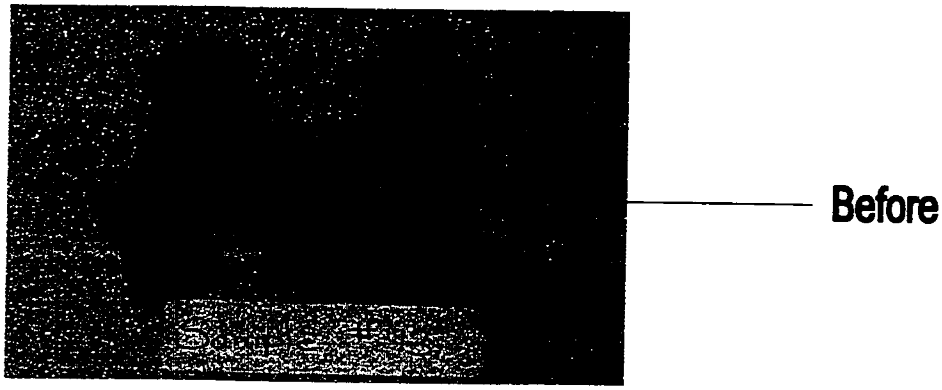


Figure 63-Wiring Harness Connectors (Before Soaking in Liquid Nitrogen)

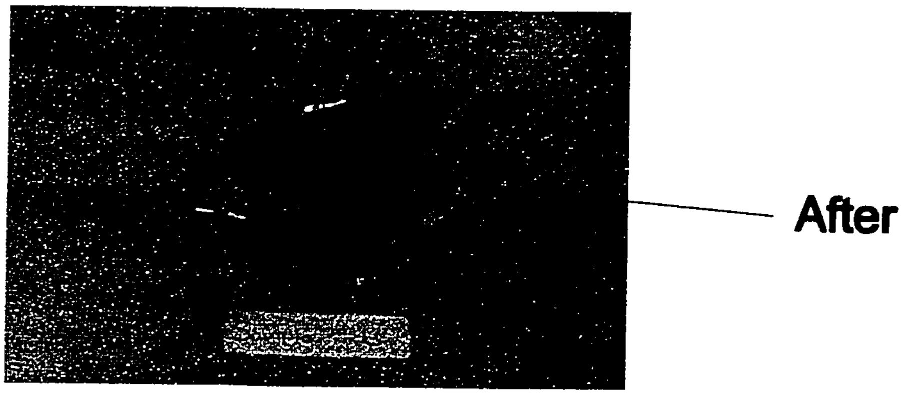


Figure 64-Wiring Harness Connectors (After Soaking in Liquid Nitrogen)

Sample #13 - Wiring Harness Connectors

This material remained in the liquid nitrogen for 20 minutes, and it was observed that the connectors were easily shattered into small pieces of plastic and aluminum/copper fragments.

Sample # 13- Wiring Harness Connectors

2 min.		no change	no change	no change
5 min.				
15 min.		crushed		
20 min.			crushed	crushed
25 min.				
45 min.				
60 min.				
1 hr 30 min.				

Table 18-Wiring Harness Connectors Test Results

The summation of these test results can be found in Table 19 below.

Summation of Test Results	
Type of Material	**Results**
Thermoplastic-Polyolefin Heat Shrinkable Tubing	**Successful**
Cable Primary Standard Wall Thermoplastic (PVC)	**Successful**
Nylon And/Or Polyester Abrasion Resistant Sleeves	Not Successful
Reflective Sleeving- Woven Braided Fiberglass- Bonded to Aluminum	Not Successful
Heavy Duty Hypalon- Insulated	**Successful**
Sleeving Braided Fiberglass	Not Successful
EPDM Bumper	**Successful**
Tape- Electrical Applications- Flame Retardent-Polymeric Coat Cloth Pressure Sensitive	Not Successful
Tape- Electrical Harness - High Temperature Resistant	**Successful**
Tape-Paper Backing- Pressure Sensitive	**Successful**
Cotton Backed Friction - Pressure Sensitive - Electrical Applications	Not Successful
Tape - Coated Cotton - Water Resistant	**Successful**
Connectors	**Successful**

Table 19-Summation of Test Results

From Table 19, it can be concluded that 8 out of the 13 different types of materials were able to reach their glass transition temperature. These results show that wiring harnesses have the potential for the ability to recover copper from them. The materials which showed no change after being soaked in liquid nitrogen will have to be removed manually prior to processing them with liquid nitrogen.

A cost analysis has been taken into account for all the wiring harness which can be retrieved from a vehicle.

There are convincing economical reasons for wiring harness recycling. Annually 9 million cars are scrapped within the European Union. These harnesses contain 90,000t of copper, 35,000t of PVC and another 20,000t of different polymers, representing a value of more than 200 million dollars - per year. You could compare numbers easily to those in Canada, having an annual production and according scrap rate of about 15 million cars and mini trucks resulting in 335 million dollars of scrap value. Therefore since we have approximately 15 kg of wiring harness in a vehicle and close to 45% of this mass is copper, this results in an average car containing approximately 9 kg of copper. Recycled copper has a value of approximately $2.20/kg. Knowing that we are able to recover 9 kg of copper, we are looking at a saving of $19.80/vehicle.

Research was conducted on the amount of time it requires to remove the wiring harness from the three major areas of the vehicle. Wiring Harnesses were removed from the engine compartment, the interior compartment and under the vehicle's body. The tools used to remove these harnesses were a pair of wire cutters or large shears. Table 20 shows the amount of time required for the removal of wiring harness from the three major areas of the vehicle. These times take into account only the removal of the harness and not the other components which have to be removed before the harness can be recovered.

[redacted]

Removal of Wiring Harness (sec.)	**1800 seconds**

[redacted]

Area	**Time to Remove (sec.)**
Dashboard	900
Headliner	300

[redacted]

Area	**Time to Remove (sec.)**
	1800

[redacted]

Table 20- Timing Chart for the removal of Wiring Harness from an automobile

Table 20 shows that it approximately required a total of 1.33 hours to remove all the wiring harnesses from a vehicle. This time does not include the time required to remove fluids from a vehicle, which is a mandatory first step which all dismantlers perform before removing any other components from the vehicle. Dismantlers usually charge between \$10.00 to \$15.00/hour to dismantle a vehicle. Knowing that it takes approximately 1.33 hours to remove the wiring and a dismantler charges \$12.50/hour, it will approximately cost \$15.96/vehicle for the removal of wiring harness from the three major locations.

[redacted]

Liquid Nitrogen PGS 60	\$200.00
(128 m^3)	
Cryogenic Transfer Hose	\$205.00
Elbow 90 degrees	\$84.00
TOTAL	**\$489.00**

Table 21 -Cost of Liquid Nitrogen

Table 21 shows the cost related for the liquid nitrogen system. Each vehicle's wiring systems can be processed through liquid nitrogen for less than a couple of pennies. The amount of nitrogen shown in Table 21 can process up to 100 vehicle's wiring systems.

5 Conclusions and Recommendations

The author's design and construction of the liquid nitrogen bath and crusher system is unique both academically and industrially. Results of the wiring harness assemblies show the very real possibility of successful development of a commercial recycling system. Most importantly, significant information identified potential problems and areas of future development to the prototype system used.

The first problem encountered was the test results showed that the sleeving and the tape currently being used on the wiring harnesses will have to be removed prior to being soaked in liquid nitrogen. These two types of material did not reach their glass transition temperature when placed in liquid nitrogen. The tape could be completely eliminated from future wiring harnesses by incorporating velcro strips to the harnesses. This would allow the harnesses to be fastened to the vehicle by velcro, eliminating the need for the adhesive tape or clips that are used to attach the harness to the vehicle frame.

The second problem encountered was the crusher system was unable to accommodate very large wiring harnesses. The need of larger rollers could be an effective way of being able to process larger wiring harnesses. More rollers situated at different heights could also be developed to produce more favorable crushing results.

These results confirm that it is possible to recycle automotive wiring harness to recover the copper by means of using liquid nitrogen. Information gained on potential problems with the construction methods, and methods of improving the materials found on current wiring harnesses will aid in assessing and realizing future designs. Finally, and most importantly, this research reveals the very real possibility of future successful development of the recovery of copper from automotive wiring harness.

By using recycled materials the automotive industry can help drive the recycling process. A substantial portion of the steel, aluminum, copper and other metals used in automobile manufacturing contains recycled material originating, in part, from automotive sources.

Through automobile manufacturers' working relationships with suppliers, increasing amounts of recycled material are being incorporated into new vehicles. Programs are being developed for plastics, metals and other materials. All materials, however, must conform to standard specifications used by the companies.
Recycled materials used in new vehicles come from both automotive and non-automotive sources. Today. plastic scrap from the manufacturing of automotive parts is recycled and used in new vehicles. Increasingly, post-consumer plastics are being used in new vehicles; for example recycled soda pop bottles are being used in automotive headliners and in some structural applications.

While these steps have been successful and are expanding, the market availability of recycled materials that meet part integrity standards has been a serious issue. There are many current and future automotive applications available to recycle-content goods (overhead consoles, sun visors, map pockets and fan shrouds, etc.), but the quantity, availability and reliability of supplies is a continuing problem. As the recycling infrastructure matures, these barriers are expected to fall.

To provide a better assessment into the development of a commercial system to recycle automotive wiring harnesses, additional material changes on current wiring harnesses should be assessed. Future work should involve replacing the materials that showed no change when placed into the liquid nitrogen bath with material having the same material properties but being able to reach a glass transition temperature.

Future work should also include working closely with current manufacturers of wiring harnesses to provide them with the results obtained during this research. A design guide should be developed to provide wiring harness manufacturers recommendations of which types of materials should be used to produce wiring harnesses and which materials should be avoided. Working closely with manufacturers of automotive wiring harness might provide future engineering design changes to switch to new material which will be able to reach its glass transition temperature.

Future work should also include further research into design changes with the current prototype system developed. The liquid nitrogen bath could be improved upon to accommodate wiring harnesses which have to be placed in nitrogen for 5 minutes and other harnesses which have to be placed in nitrogen for over two hours.

Future work should also include modifications to the crusher system. The addition of more larger rollers to the system would assist in more favorable results in less time. There is also the possibility of future research into using vibration methods to shatter the plastic from the copper wire.

Finally, future work should include further attempts to reduce the cost of the system. It is quite clear that the recycling of wiring harnesses can be very costly.

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